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Technology for Pressure-Instrumented Thin Airfoil Models

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FINAL REPORT ON PHASE 1 OF NASA CONTRACT NAS1-17571

"TECHNOLOGY FOR PRESSURE-INSTRUMENTED THIN AIRFOIL MODELS"

PROJECT SUMMARY

The objective of Phase 1 of this research was to identify, then select and evaluate, the most appropriate combination of materials and fabrication techniques required to produce a Pressure Instrumented Thin Airfoil model for testing in a Cryogenic wind Tunnel (PITACT). Particular attention was to be given to proving the feasability and reliability of each sub-stage and ensuring that they could be combined together without compromising the quality of the resultant segment or model. In order to provide a sharp focus for this research, experimental samples were to be fabricated as if they were trailing edge segments of a 6% thick supercritical airfoil, number 0631X7, scaled to a 325mm (13in.) chord, the maximum likely to be tested in the 13in. x 13in. adaptive wall test section of the 0.3m Transonic Cryogenic Tunnel at NASA Langley Research Center.

The majority of these objectives were achieved in Phase 1. Specifically it was shown that;

-EDM (Electro-Discharge-Machining) by the wire-cut process was a cost-effective technique for cutting profiled bond planes and airfoil contours in 300 series stainless and 18 nickel 200 grade maraging steels.

-Chemical milling was a highly cost-effective technique for creating a complex network of channels in the surfaces of plates of these two metals. Initial samples were flat plates, but subsequently it proved possible to create matched pairs of channels on both the concave and convex surfaces of profiled bond planes.

-Orifices of high definition have been produced by the technique of pre-drilling blind holes from the ends of the chemically-milled channels, such that they subsequently outcrop in the airfoil surface when its profile is EDM wire-cut.

-Vacuum brazing has been used to join together the plates with the channels and orifice holes pre-formed into their surfaces. Well bonded plates with unblocked channels were achieved in small samples with flat bond planes, but fixturing problems with samples having profiled bond planes caused cross-leaks between channels. For small samples these problems are readily soluble, but for larger plates warpage, caused by the relief of residual stresses, is more serious.

-Grain growth in 18 nickel 200 grade maraging steels occurs at brazing temperatures above 1000C (1830F). Good bonds have been made with this material using a nickel-palladium-silicon alloy, Metglas MBF 1005.

-Joints between trailing edge segments and the main airfoil have been investigated using a comb and docking port configuration.

Potential commercial applications of this research will occur initially in the construction of highly instrumented airfoil models for use in cryogenic and conventional wind tunnels. The opportunity for quality control at intermediate stages of fabrication should make it a cost-effective technique. It is also probable that some, or all, of these technologies would be usable in other applications requiring accurately formed channel networks.

FINAL REPORT ON PHASE 1 OF NASA CONTRACT NAS1-17571

"TECHNOLOGY FOR PRESSURE-INSTRUMENTED THIN AIRFOIL MODELS"

INTRODUCTION

Optimization of the choice of material and fabrication techniques for construction of models for cryogenic wind tunnels such as the U.S. National Transonic Facility and the NASA 0.3-m Transonic Cryogenic Tunnel has presented designers with an almost insuperable problem. Many of the properties required are near the limits attainable with state-of-the-art technology, and in many cases improvements in one direction seem inevitably to be accompanied by losses in others. For example, the material has to have a yield stress high enough to carry the imposed aerodynamic loadings, yet be tough enough to operate safely at cryogenic temperatures.

The need for adequate strength and toughness for safe operation at cryogenic temperatures severely limits the range of materials available for model construction. In order to meet the minimum acceptable toughness requirements, many high-strength materials have to be heat-treated to a lower strength condition and this can lead to dimensional instability, either as a result of the formation of an unstable metallurgical structure, or due to the stresses induced on cooling from the heat-treatment temperature.

The chosen material also has to be capable of being fabricated using available machining and joining techniques to give a dimensionally stable model with a precisely known shape. However, most conventional fabrication techniques create, to a greater or lesser extent, tensile or compressive stresses in the material, and in many cases they also result in a localized modification to the microstructure of the material. Considerable warpage can be caused either by the creation or relief of these stresses during model fabrication or stress relieving heat-treatments, while additional dimensional instability can be caused by the strains induced by differential thermal contraction during temperature cycling between room and cryogenic temperatures.

In order to generate valid aerodynamic data the airfoil surface must have a high quality finish which also has to be either intrinsically resistant to, or capable of being protected against, corrosion and degradation. If the airfoil is to be of maximum use in providing aerodynamic information, it must, in general, be fitted with a complex array of pressure orifices, tubes and sensors of various types such as heat transfer gauges, transition detector gauges and temperature measuring devices. One aspect of particular concern is the method of achieving the necessary connections between orifices drilled into the airfoil surfaces to measure the pressure distribution over the airfoil and the measuring equipment generally located remote to the model. Typical current practice is to machine a recess into one surface of the airfoil to expose the bottom of the pressure tappings, braze fine diameter tubes to connect with each individual orifice and then lead a bundle of such tubes out via the wing root or support sting. The aerodynamic profile of the model is then restored by welding a cover plate, usually fitted with its own pressure orifices, over the recess. Alternatively, large channels are routed out of the airfoil surface, bundles of tubes are then laid in these channels

and the gap backfilled with some form of filler which is then re-profiled to the airfoil contours. This technique is, however, unlikely to be particularly successful for thin airfoils used in cryogenic wind tunnels because of differential contraction between the different materials. Furthermore, these are labor intensive, and therefore expensive, methods of construction. Mistakes which occur in the latter stages of model fabrication, where the added value is high, are particularly expensive. The problem is, perhaps, at its most severe in thin airfoils typical of advanced fighter configurations, particularly at the trailing edge where thicknesses can be of the order of 0.040 inch. Hitherto, for example, in such models for the 0.3-m TCT, it has not been possible to provide an adequate array of pressure orifices at locations between 80 and 100 percent of chord using conventional construction techniques.

Initial research and development of an alternative approach to airfoil fabrication has been carried out by NASA LaRC personnel and the principal investigator for the last 4-5 years. In essence, it involves machining a network of open channels into the surface of two flat plates which are subsequently vacuum brazed together to form closed, pressure-tight passages. These passages form connections between holes pre-drilled into the plates at one end of each channel and a take-off point at the edge of the airfoil. The passages are then pressure tested for cross-leaks before further expense is incurred in profiling and finishing the airfoil surfaces: if the channels are not pressure-tight the model can be aborted at this relatively inexpensive stage.

The initial research was conducted using 15-5PH, 17-4PH, type 347 and Nitronic 40 stainless steels with electrodeposited coatings or thin foils of copper as the braze material. Further work was concentrated on the use of a nickel-based alloy, MBF 20 (AWS BNi2, AMS 4777A) and the development culminated in the fabrication of a symmetrical airfoil with a planar bond line made from 15-5PH stainless steel and vacuum brazed with MBF 20. This development was, however, only partially successful as warpage, caused by the relief of residual stresses in the plates, created numerous cross-leaks between adjacent channels.

The research and development carried out during Phase 1 of this program is essentially a continuation of this earlier work, but targeted towards a more difficult set of requirements, namely development of the technologies needed to locate orifices in and near the thin curved trailing edges of airfoil models intended for testing in cryogenic wind tunnels.

PHASE I TECHNICAL OBJECTIVES

The essential objective of Phase I was to identify and then select and evaluate the most appropriate combination of materials and fabrication techniques required to produce a Pressure Instrumented Thin Airfoil model for testing in a Cryogenic wind Tunnel (PITACT). Particular attention was given to proving the feasibility and reliability of each sub-stage and ensuring that they could be combined together without compromising the quality of the resultant segment or model. Some specific problems to be addressed were:

- Materials - The choice of suitable materials was driven, primarily, by the need to have adequate strength and toughness for cryogenic operations. Currently favored choices are A286, 18 nickel 200 grade maraging steel (Vascomax 200) and Nitronic 40, and these, together with Hastalloy X and type 321 stainless steel were the materials selected for initial study. Samples from the 300 series of stainless steels were also used extensively as the short, 7 month, period of performance for Phase I dictated the use of readily available materials for the initial evaluation of techniques such as EDM wire cutting and chemical milling.

- Contour Machining - Conventional metal removal techniques such as milling and grinding induce residual surface stresses that can cause deformation of the whole piece. However, some machining techniques, such as electro-discharge machining (EDM) and chemical milling, are essentially stress-free, and an important part of Phase I was to evaluate these techniques for potential use on the PITACT model. In particular, the wire EDM technique was to be closely studied for creating profiled bond planes and airfoil surfaces.

- Formation of Channels & Orifices for Pressure Instrumentation - The aim of producing pressure instrumentation in the thin trailing edge at locations from 80-100 percent chord ruled out the use of conventional techniques such as plumbing-in small diameter tubes. Alternate approaches were therefore to be used to form connecting channels within the limited thickness of material available and without compromising the structural integrity of the model. Initial studies were to be carried out on bonding together plates with pre-machined holes and channels, but the majority of the Phase I effort was to be concentrated on proving and refining the formation of channels by chemical milling.

- Bonding & Joining Methods - A number of alternative methods are available for bonding plates with pre-formed channels, or joining together subcomponents of a complete model. Suitable combinations of base material and bonding agent needed to be evaluated for the candidate materials to ensure that reliable bonds could be formed that would stand up to the stresses subsequently applied during later fabrication stages and during the thermal cycles that a model has to undergo between room temperature and its cryogenic operating environment. Particular attention needed to be given to finding a brazing alloy that permitted Vascomax 200 to be vacuum brazed without degrading its metallurgical structure.

- Finishing & Assembly Methods - One continual problem with model manufacture is the increasing risk and cost of failure in one of the latter fabrication stages that can result in the degradation or total loss of the model for useful aerodynamic research. This risk is greatest in the case of relatively thin airfoils ($t<0.10c$) and modular assembly techniques were therefore to be evaluated to allow particularly critical regions to be fabricated as sub-assemblies which could then be joined together to create the final model configuration. If successfully developed, this modular approach could also allow the replacement of damaged segments or even the easy reconfiguration of a model to study, for example, different trailing edge or flap configurations.

In order to provide a relevant focus for the research and development effort, a specific airfoil configuration was chosen as a typical representative of its generic class. Airfoil number 0631X7 has a maximum thickness of 6% of its chord, and when scaled to a chord of 325mm (13in.), which is the maximum likely to be used in the LaRC 0.3m TCT with the adaptive wall test section, the trailing edge thickness is 1.3mm (.052in.).

The specific objective of Phase 1 of the PITACT program was therefore set to develop the technologies necessary to place a high density of orifices at locations from about 80% to 100% of chord in a spanwise segment of this supercritical airfoil profile, and to create a network of pressure-tight passages that connected these orifices to suitable joints at the forward edge of the segment.

The shape of this airfoil, number 0631X7, and the trailing edge segments fabricated in the Phase 1 effort are shown in Fig. 1.

-REPORT STRUCTURE

The technical details in this report are presented in such a way as to reflect the logical and progressive development of the research and development carried out in phase 1 of the PITACT program. Thus the subsequent sections document the following progression;

- -DEI series : Flat plates of 5 candidate materials with machined channels and brazed with MBF 20.
- -RH series : Flat plates of 300 series stainless steel with chemically-milled channels and brazed with MBF 20.
- -DS1 sample : Block of 304 stainless steel with EDM wire-cut, profiled bond line, chemically-milled channels on the convex surface, vacuum brazed with MBF 20, and with airfoil contours EDM wire-cut onto the upper and lower surfaces of segment 4M.
- -Metallurgy of Vascomax 200 : Evaluation of various brazing alloys to identify MBF 1005 as giving a good bond without causing excessive grain growth in the parent metal.
- -DS2 &3 samples : Vascomax 200 blocks with EDM wire-cut profiled bond line, chemically-milled channels on both concave and convex surfaces, vacuum brazed with MBF 1005, and with airfoil contours cut on their upper and lower surfaces.

The details of the various samples used in Phase 1 of the PITACT program are summerized in Table 1, while further details are given in Appendix 1, Tables A2 to A9. Copies of the most relevant working drawings, reduced where appropriate, are given in Appendix 2 for reference.

Much of the technical information discussed in this report is presented in Figs. 2 to 14, the originals of which are color photographs. Some copies of this report have been prepared with black and white photocopies taken from these originals. Should color reproductions be required, they can be obtained from the technical monitor, Dr. R.A.Kilgore, Mail Stop 287, LaRC, Hampton Va. 23665.

DEI SERIES OF SAMPLES

Flat plates of A286, Nitronic 40 (21Cr-6Ni-9Mn) Hastalloy X, 18 Nickel 200 grade maraging steel (Vascomax 200) and type 321 stainless steel were machined to size 50x50x6mm (2x2x0.25in.) and their surfaces were ground flat and parallel. A pattern of channels, 0.25mm wide x 0.25mm deep and spaced at 5mm centers (.010in. wide x .010in. deep at 0.2in. centers) was electro-discharge machined into the surface of one sample of each type of material, designated a DEI A series plate, as shown in Fig. 2a. Four holes, each 0.5mm (.020in.) diameter were drilled at the ends of the channels that did not completely span the plate, and a similar group of four holes were drilled in the matching DEI B series plates as shown in Fig. 2b. Two holes, 3.7mm (.15in.) in diameter were drilled in each plate to accept the locating dowels which kept the two plates in alignment during vacuum brazing.

MBF 20 (AMS 4777B, AWS BNi2) braze alloy foil, thickness 0.037mm (.0015in), was placed between the pair of plates, which were then loaded into a vacuum furnace. The temperature was increased to 1065C (1950F) in 30 minutes, held for 15 minutes and then furnace cooled over a period of 2 to 3 hours.

A view of one edge of each of the samples of A286, Vascomax 200, Hastalloy X and Nitronic 40 after vacuum brazing is shown in Fig. 2c. It can be seen that a brazed bond exists at this end of each of the pairs of plates. However, as may be seen more clearly from Fig. 2d, a simple operator error by the brazing subcontractor resulted in each Hastalloy X plate being paired with a Nitronic 40 plate to form two mismatched pairs. The differential expansion set up during the brazing cycle caused the dowel pins to bind and the plates to warp, as may be seen from the elliptical shaped gap between the two back-to-back samples in the bottom half of Fig. 2d. Dowel binding also occurred with the A286 samples to leave a wedge-shaped gap between the plates, with a good bond at one end only. In the case of the Vascomax 200 sample a good metallurgical bond was formed across the whole plate, but the channels were blocked and excessive grain growth occurred in the parent metal. Only the 321 stainless steel samples had a good bond over the whole plate and un-blocked channels.

RH SERIES OF SAMPLES

Two type 316 stainless steel plates, sized 80 x 60 x 6mm (3.2 x 2.4 x 0.25in) were cut to shape, lapped flat and degreased in preparation for chemical milling the pattern of channels that can be seen in Fig. 3a. A mask 4 times full scale was drawn to the required pattern, photographed and reduced down to to full size for application to a photo-sensitive lacquer that had been applied to the surface of the stainless steel plates. Unfortunately the mask was, in the event, over reduced so that channels that should have been at 3mm centers, were actually at 2.4mm centers. The plates were developed to remove the lacquer from the regions that were to become channels, while leaving it to protect the remaining area of the plates. Hot acidic ferric chloride solution was used to chemically mill the channels to the required depth. After washing off excess ferric chloride and drying, the lacquer was removed with solvent to reveal the unattacked surfaces that subsequently became the faying (bonding) surfaces.

A series of holes of diameters 1.0, 0.5 & 0.32mm (.040,.020 & 0.013in) were drilled at the ends of the channels, as may be seen in Fig. 3a, and at higher magnification in Fig. 3b, for sample RH2. A similar sized plate, LJS3, also with its surfaces lapped flat, was matched to RH2 and holes were drilled through both plates to take the 2mm (.080in) dowel tubes used to align the two plates during brazing.

MBF 20 brazing foil, 0.37mm (.0015in.) thick was placed between the faying surfaces of the two plates. Thin strips of 0.05mm (.002in.)thick nickel foil were placed at the edges of the faying surfaces to shim them apart and thus maintain a constant separation during brazing. The assembly was placed in a vacuum furnace with a small weight on top of the plates to keep a light pressure on the nickel shim. The temperature was raised to 1065C (1950F) in 30 minutes and held there for a further 30 minutes before furnace cooling. Sample MG7 thus formed was found to have a good metallurgical bond between the two plates and the center through-channel was unblocked.

Fig. 3c shows the locations of the offcuts formed by EDM wire-cutting the edges from the sides of sample MG7 to form segment 3M. Also clearly visible is the vertical section wire-cut through the slit-sawn channels at the top edge of the sample. (The slit-saw cuts were used to extend the chemically-milled channels to the edge of the plates.) The excellent channel definition obtained by wire-cutting through the channels is revealed more clearly by the X20 magnification view in Fig. 3d.

The offcut 3A was polished and lightly etched to reveal the metallurgical structure of the brazed bond line as shown in the X70 magnification view in Fig. 4a. The grain boundary decoration visible in the zone adjacent to the bond line is as expected, and due to the migration of silicon, a sigma phaze former, from the braze alloy.

In order to obtain a taper section through the bond line, a planar surface was wire-cut at an angle to the bond plane, which also exposed the orifices in, and adjacent to, the trailing edge. This is shown in Fig. 4c, and at the higher magnification of X10 in Fig. 4d. Although there appear to be a few small imperfections in the braze zone these are probably polishing artifacts as they are also present in the parent metal. The high quality of this taper section is significant because in an actual model or segment it might be necessary to have a bond line outcropping on the airfoil surface. An even higher magnification view of this region is shown in Fig. 4e, in which the grain boundary decoration adjacent to the brazed zone is again visible.

Two further planar surfaces were then ground onto the upper surface of segment 3M in order to cut through the blind holes that had been pre-drilled in RH2 and the orifices thus formed are visible in Fig. 4b. One of the small 0.32mm (.013in) orifices was found to be blocked with braze alloy, while a further orifice is missing because the drill work-hardened the stainless steel and failed to penetrate.

Nevertheless, this segment represented a significant achievement in that 15 out of a possible 17 channels connected with clear orifices, including the one that would have out-cropped in the trailing edge. Thus in an actual model or segment these would have been usable for boundary layer pressure measurement.

SAMPLE DS1

As noted earlier, the objective of Phase 1 of the PITACT program was to be able to place pressure orifices and their interconnecting channels in the thin trailing edge of airfoils such as the 6% chord number 0631X7. As the trailing edge of this airfoil has a pronounced downwards curvature it is necessary, therefore, to be able to create a similarly profiled bond plane at, or near, the neutral axis of its airfoil section. Sample DS1 was used to investigate the feasibility of EDM wire-cutting a profiled bond plane, chemically milling channels onto a curved surface and vacuum brazing together plates with curved faying surfaces.

A piece of rectangular stainless steel, 25mm (1.0in) thick, was rough machined and ground to size 135 x 75 x 24mm (5.4 x 3.0 x 0.96in). The profile shown in Fig. 1b was chosen for the bond plane and EDM wire-cut into the block. The resultant two halves, DS1 A&B, are shown in Fig. 5a, together with a piece of the 0.37mm (.0015in) thick MBF 20 braze foil. When the two halves were placed together after EDM wire-cutting it was found that the gap between them was not of constant thickness, being zero in the planar section and increasing to about .25mm (.010in) at the trailing edge. This was due to the thickness of the wire used in the EDM machine and the fact that the two surfaces were created by opposite sides of the wire. With samples DS1 A&B it was possible to achieve a zero gap over the bond plane by shifting DS1A towards the trailing edge by about 1mm (.040in) relative to DS1B. On a more complex shape this would not, however, be possible and it would be necessary to recut one of the two surfaces with the co-ordinates accurately aligned on the opposite side of the wire.

A pattern of channels spaced at 3mm (0.12in) centers was chemically-milled onto the convex surface of sample DS1A as shown in Fig. 5b. The sub-contractor experienced some difficulties in getting a well defined image exposed onto the lacquer on the curved part of the bond plane, and as a consequence the channels were not properly formed in this region. For subsequent samples, ways were found to overcome this problem, but at this stage the interim solution was to rework the channels with a triangular needle file to ensure that they would be adequate to allow the samples to go forward to the vacuum brazing process. The average channel width was about 0.4mm (.016in) and the depth about 0.25mm (.010in).

A series of holes were drilled at the ends of the channels: 0.037mm (.013in) nearest the trailing edge, 0.5mm (.020in) further forward and 1.0mm (.040in) for the foremost orifices. Fig. 5c shows at X4 magnification some of the channels with the 0.32 and 0.5mm holes drilled at their ends. Also visible at the top of Fig. 5c is a pattern of channels intended for use in locating the position of the trailing edge. This is necessary because it is prudent to work with samples larger than the ultimate size of the segment so that the edges can be cut off, both for use in quality control of the brazed bond and also to protect for as long as possible the thinner parts of the segment. The two views given in Fig. 5d show more detail of the channels and 0.32mm holes at magnifications of X15 and X20.

The two halves DS1 A&B were then placed together, with the 0.037mm (.0015in) thick MBF 20 brazing foil sandwiched between them, and held under pressure in a press while a series of laser tack-welds were made along the sides at the bond plane. This stage is shown in Fig. 6a in the upper view,

the lower view illustrating the excellent definition obtained when the PITACT name and date were chemically-milled onto the side of sample DS1. After brazing, the sides and ends of the sample, by now designated MG8, were wire-cut off to allow evaluation of the quality of the brazed bond and to create segment 4M of the required size. It was soon apparent that the gap established and held by the laser tack-welds was approximately twice the thickness of the braze foil, i.e. 0.075mm (.003in) for the average gap width. As a result there were cross-leaks between channels, some indication of which can be seen in the longitudinal sections shown in Fig. 6b. A better view is, however, seen in the transverse section shown at a magnification of X3 in the upper part of Fig. 6c. The oversized gap meant that there was simply not enough braze alloy to ensure that the bonds between adjacent channels contained enough braze alloy either to prevent cross-leaks or to create a full-strength bond. Nevertheless, bonding at the trailing edge was much better and the view given in the lower part of Fig. 6c at magnification X15 shows both the improved bond line and the unblocked channel that outcrops in the trailing edge. (Both of the views in Fig. 6c are taken with the material in the as-wirecut condition.)

The final fabrication stage carried out on this sample was to EDM wire-cut the upper and lower airfoil contours to the co-ordinates of the trailing edge segment shown in Fig. 1b, that is for airfoil number 0631X7 scaled for a 325mm (13 in. chord). Fig. 7a shows segment 4M as wire-cut from sample MG8 together, with offcuts from the upper and lower surfaces. Longitudinal sections were taken from segment 4M in such a way as to expose both channels and orifices, and one such section is illustrated in Fig. 6d. The X16 magnification view, at the top of Fig. 6d, shows a channel connecting to a 0.32mm (.013in) orifice, and the location of this orifice with respect to the trailing edge is shown at X4 in the lower view. One feature emphasized by the X16 view is the need to deepen the connecting channels so as to increase their area of cross-section and minimize the pressure drop from orifice to the measuring device.

An indication of the surface finish obtained by EDM wire-cutting can be obtained from the views shown in Figs. 7b and 7c. There are two possible causes of the linear features prominent in both photographs. The first is due to the way in which the profile co-ordinates were fed into the EDM wire-cut program. It is likely that the programmer only used co-ordinates spaced at about 2 or 3mm intervals, and that the curve splining program connected them up with circular arcs or straight lines. This is the most probable explanation for most of the linear features seen in Figs. 7b and 7c. However, even with flat planar cuts with an EDM wire, linear features are created when the wire passes through an electrical discontinuity as this alters the power of the spark discharge. The drilled orifices represent electrical discontinuities and thus can give rise to linear features such as those observed, although the effects are minimized with small diameter orifices. The larger channels do, however, create more serious discontinuities and deeper scoring. (See, for example, the scoring on offcut 3A shown in Fig. 3c.) As noted earlier, holes of three different diameters were drilled at the channel ends, 0.32, 0.5 and 1.0mm (.013, .020 and .040 in), and the orifices they formed on the lower airfoil surface are clearly shown in Fig. 7c. An impressive illustration of the clean outline of the orifices formed by wire-cutting through pre-drilled holes can be seen from the X20 magnification views of the three orifices sizes shown on the right of Fig. 7b. The view on the left of Fig. 7b shows the location of the orifice in the trailing edge, marked with an arrow, as well as some of the orifices on the lower airfoil surface.

Once all the available information had been gleaned from segment 4M, it was put to one further use, that of demonstrating one possible method of connecting trailing edge segments to the main wing section. To this end a comb with teeth, 2mm (.080in.) square and at 4mm (.160in.) centers, was cut onto the forward end of the segment. The 4mm spacing of the teeth was necessary to match up with the similarly spaced docking channels formed in segment 3F to be described in the next section. For such a system to work in a real situation, the channels in both segments would have to have the same spacing, but in the present case the channels in 4M were at 3mm centers and those in 3F at 4mm. The black dots visible in the center of the teeth, viewed end-on in the inset to Fig. 7d are marks put on to indicate the positions at which the channels should occur, namely in the center of each tooth in the male comb.

THE LJS/RH TRIPLET

In adopting the concept of modular construction of airfoils from smaller segments, an implicit commitment was incurred to investigate possible arrangements for joining segments to the main airfoil structure. Such joints would have to accomplish two simultaneous objectives;

- achievement of a good load-bearing mechanical joint that would permit accurate alignment of the segment with the main airfoil, in such a way as to maintain the correct location and profiles of the airfoil surfaces.

- achievement of pressure-tight connections between the channels in the segment and those in the main airfoil that will stand up to the stresses imposed by aerodynamic loading and temperature cycling to and from its cryogenic operating environment.

The LJS/RH triplet sample was designed to investigate one possible jointing configuration that could be fabricated using the technologies thus far developed during Phase 1 of the PITACT program.

Two flat plates of type 304 stainless steel, 6.25mm (.25in) thick and designated LJS 1 and LJS 2 respectively, were lapped such that their faces were flat and parallel. Docking ports 2mm (.080in) wide by 8mm (.32in) long were milled to a depth of 1mm (.040in) into the surfaces of both plates as shown in Fig. 8a and 8b. A 7mm (.28in) wide flat, also 1mm (.040in) deep was milled in front of the docking channels to form one side of the groove in a tongue and groove joint. Channels, 0.5mm (.020in) wide and 0.5mm (.020in) deep were slit sawn from the ends of alternate docking ports to the opposite edges of the plates, as shown in Fig. 8b. When the two plates were placed together they formed a series of 2mm (.080in) square docking ports at the inner end of the 7mm (.28in) wide groove. An end-on view of the docking ports thus created is shown in the top view of Fig. 8c.

In the event, both plates warped when channels were slit sawn into their surfaces due to the relief of residual surface stresses. The plates were therefore heat-treated to anneal any remaining stresses, then re-milled to deepen the docking ports and groove to the requisite 1mm (.040in). A further stainless steel plate, RH1, that had a pattern of channels chemically milled into its surface to the same configuration as that shown previously in Fig. 3a for RH2, was added to plates LJS1 and 2 to form a triplet. A series of 1.0,

0.5 and 0.32mm (.040, .020 and .013in) holes were drilled at the ends of the chemically-milled channels to represent orifices that would need to be present in an actual airfoil. 2mm (.080in) clearance holes were drilled through the three plates to accept the 2mm diameter, thin-walled stainless steel tubes used as dowels to align the three plates.

Foils of MBF 20 braze alloy, 0.037mm (.0015in) thick, were placed between the two sets of faying surfaces and pieces of 0.05mm (.002in) nickel foil were used to shim the faying surfaces apart when the braze foil melted. The assembled triplet was placed into a vacuum furnace, a weight was placed on its top to keep some pressure on the nickel shim and they were brazed at 1050C (1920F). The resultant brazed triplet, designated MG6, is shown in the lower view of Fig. 8c.

Examination of the brazed triplet showed that some further warpage had occurred during brazing with the result that some of the central channels were blocked. The 2mm (.080in) wide, 7mm (.28in) deep groove was re-milled to a width of 4mm (.16in) to accommodate the tongue cut on the forward section of segment 4M and the four sides were ground flat. The upper and lower surfaces of the triplet, now designated segment 3F, were contoured to match the upper and lower contours of segment 4M and so produce the dockable segment to be described in the next section. A view of segment 3F showing the docking ports and cross-feed channels is given in Fig. 8d.

One particular lesson to be learned from the experience obtained from fabricating segment 3F highlights the problem of warpage caused by the creation or relief of residual stresses. The problem is going to be more severe in thinner plates because the deflection produced for a given surface stress is inversely proportional to the plate thickness. Thus, the economic attraction of using thin plates to minimize the amount of redundant metal has to be balanced against the greater probability of warpage that could cause the whole component to be rejected.

Nevertheless, the fabrication of segment 3F represented another step forward, in that two good metallurgical bonds were formed simultaneously between the 3 plates. The partial blockage that occurred in some of the channels between plates LJS1 and 2, was capable of rectification by drilling the excess braze metal from the channels.

A DOCKING SYSTEM TO JOIN SEGMENTS TO THE MAIN AIRFOIL

The need for investigation of a possible configuration for a docking system was explained at the beginning of the previous section, and the fabrication of segments 4M and 3F has been described. Fig. 9a shows segment 3F, on the left, and segment 4M, on the right, before docking, while Fig. 9b shows the pair after docking. An even better idea of the design of the joint can be obtained from Fig. 9c which shows the situation where segment 4M has been shifted laterally by one tooth. The male tooth can be seen penetrating into the section cut through one of the docking channels, while the thicker 4mm (.080in) tongue fits into its matching groove. A low melting point solder or adhesive resin would be necessary to ensure a pressure-tight joint between tooth and docking port, so that their associated channels did not leak.

Similarly, some form of mechanical fastener and/or bonded joint would be needed to lock the tongue and groove to form a load-bearing mechanical joint. The views shown in Fig. 9d are unfortunately rather dark, but it is possible to see that the upper two sections taken from segments 4M and 3F are undocked. The sections through segments 3F (left) and 4M (right) shown in the lower view of Fig. 9d are as-docked.

Experience gained in fabricating this design of a docking system has shown up a number of possible difficulties and it is unlikely that it would be used to join trailing edge segments to an actual airfoil model. In particular, the need for mechanical strength and stiffness from the tongue and groove joint might conflict with the application of the solder or resin needed to form a pressure-tight joint between the teeth on the trailing edge segment and the docking channels in the main airfoil. Further designs would therefore need to be evaluated in Phase II.

METALLURGY OF 18 NICKEL 200 GRADE MARAGING STEEL

As part of the initial series of tests, samples DEI 4A&B were vacuum brazed at 1050C (1920F). While sample DEI4C was kept as a control. Comparison between sections taken from both heat-treated and control samples, polished and etched to reveal their metallurgical structures, showed that significant grain growth had taken place during the brazing operation. This is shown clearly in Fig. 10c by the X400 magnification metallographs. The structure of the control sample on the left is as would be expected for an 18 Nickel maraging steel, basically a lath martensite. The heat-treated sample on the right shows an equiaxed grain structure with strong grain boundary decoration. Such a material would have a significantly lower fracture toughness at the cryogenic operating temperatures of an actual wind tunnel model.

A series of 18 Nickel maraging steel test samples were brazed using alloys that melt at lower temperatures. Work carried out at NASA Langley Research Center has shown that temperatures should not exceed about 1000C (1830F) if grain growth is to be avoided. The four alloys chosen were available as foils, 0.037mm (0.0015in.) thick from Metglas, Parsippany, New Jersey. Metallographs at magnifications of X400 from sections taken from the four samples are shown in Figures 10c and 10d, while the structure of the control sample is shown in Figure 10b at the same magnification. The lowest brazing temperatures were for the two alloys shown in Fig. 10c. MBF 1005, an experimental nickel-palladium alloy was brazed at 927C (1700F) and the structure of its bond can be seen on the left of Fig. 10c. There is some second phase present in the braze zone, but it is not too massive and does not span the bond completely. Furthermore there is no apparent change in the grain structure of the parent metal, as may be seen by comparison with Fig. 10b. This alloy was therefore chosen for further work with samples DS2 and DS3.

The metallograph on the right of Fig. 10c is of the brazed bond formed using MBF 65A,(AWS BNi7) a nickel-phosphorous alloy that was brazed at 982C (1800F). There is some indication of modification to the grain structure, especially near the braze zone, but less so in the parent metal. A more serious objection to the use of this alloy is, however, the 9% phosphorous considered by the technical director of the material suppliers, Vasco Teledyne, likely to cause problems with the parent metal and hence this braze alloy was rejected from further consideration.

The two other braze alloys tested both contained boron and metallographs of their joints are shown in Fig. 10d at X400. The dark etching nature of the zone adjacent to the braze zone and the heavy grain boundary decoration further into the parent metal are caused by the rapid diffusion of boron from the braze alloy. The more aggressive nature of the liquid metal is also evident from the greater degree of intergranular penetration in these two alloys as compared with those in Fig. 10c. Even more significant, however, is the equiaxed grain structure of the parent metal caused by the higher, 1010C (1850F), brazing temperature. These two alloys, the nickel palladium MBF 1002 shown on the left of Fig. 10d and the modified MBF 20 shown on the right, were therefore eliminated from further consideration.

On the basis of these tests, the 47Ni-47Pd-6Si MBF 1005 was chosen for further study with the 18 nickel maraging steel samples DS2 and DS3 to be described in the next section. On the advice of the Metglas metallurgists, two different brazing temperatures 927C (1700F) and 965C (1770F) were chosen to see whether the greater fluidity available at the higher temperature would be an advantage or disadvantage as regards bond formation or channel blockage. As will be seen, however, these questions were largely left unresolved because of fixturing problems encountered with these samples.

18 NICKEL MARAGING STEEL SAMPLES DS2 AND DS3

Thus far in Phase 1 of the PITACT program, the complexity of the samples has progressed from flat plates of 300 series stainless steel with machined and chemically-milled channels, to a 304 stainless steel segment with a profiled bond plane and channels chemically milled into the convex side of the bond plane. The metallurgical limitations imposed by grain growth in 200 grade 18 nickel maraging steel have been evaluated and a suitable braze alloy has been identified to allow the construction of realistic trailing edge segments from this high strength alloy of major interest for the construction of airfoil models for cryogenic wind tunnels. Samples DS2 and DS3 were intended as a culmination of the Phase I effort on the PITACT program by the actual fabrication of two such segments.

Two blocks of Vascomax 200 were obtained from Vasco Teledyne with the kind assistance of their research director. The two blocks supplied were rectangles, sized 125 x 75 x 12.5mm (5 x 3 x 0.5in.) and when rough machined and ground with parallel sides they measured 120 x 70 x 11mm (4.8 x 2.8 x 0.44in.). A profiled bond plane was then EDM wire-cut through each of the blocks using the same trailing edge coordinates as used for sample DSI, but making the necessary adjustments to ensure that the trailing edge lay within the 11mm (.44in.) thickness. The two halves thus created, DS2A and DS2B are shown replaced together in Fig. 11a. (The corresponding halves of DS3 are just visible at the right-hand side of Fig. 11a). In Fig. 11b, DS2A and B are shown opened out to give an idea of the degree of curvature on the bond plane.

Using the same basic techniques as before, photographic masks were made of the channel pattern required, but in this case a matched pair was created for application to both convex and concave surfaces as may be seen in Fig. 11c. Creating a sharp image on the concave surface presented a challenge to the lithographers, but high quality images were obtained in the lacquer coatings on both surfaces. Chemical milling using acidic ferric chloride had already been shown to be effective in small-scale tests with Vascomax 200

and excellent channel definition was achieved in all four samples. Fig. 11d shows three of the channels formed on the concave surface of DS2B, and it also gives an indication of the degree of curvature in the bond line.

Chemical milling channels approximately 0.4mm (.016 in) thick is accompanied by a significant degree of undercut beneath the surface of the adjacent lacquer and this gives rise to the apparently ragged appearance of the channels shown at X4 magnification in Fig. 12a. However, simple hand reworking with a triangular needle file produces the much cleaner and highly regular channel definition shown in Fig. 12b. The photo-sensitive lacquer was in fact left on the sample surfaces until all machining operations were complete, as it was found to be extremely tough and an excellent protective coating for the faying surfaces.

Careful attention was paid to mask alignment while the samples were prepared for chemical milling and when the two halves of DS2 were placed together before bonding an excellent match was achieved such that the two semi-circular half channels formed complete channels with almost circular cross sections as shown in the upper view of Fig. 12c. The lower view in Fig. 12c gives a clear impression of the regularity and definition of the channels at the forward edge of the samples.

As noted earlier both samples DS2 and DS3 were brazed using the nickel-palladium alloy MBF 1005. DS2 was brazed at 927C (1700F) to give sample MG13, while DS3 was brazed at the higher temperature of 965C (1770F) to produce MG14. Dowel pins, 2mm (.080in) in diameter, were used to align the two halves of each sample and once again 0.05mm (.002in) thick nickel shim was placed at the sides of each sample to produce a gap of constant thickness larger than the 0.037mm (.0015in) MBF 1005 braze foil. A weight of 1.15kg was placed on top of the sample to keep some pressure on the shim during brazing and the samples were heated to the brazing temperature in about 20 minutes and held there for 15 minutes. The relatively long time taken in furnace cooling after brazing meant that the samples spent a significant period passing through the ageing temperature range and that they were at least partially aged. A full cycle of solution annealing followed by quenching and ageing would, therefore, probably be necessary to achieve maximum strength.

For some reason, as yet not fully understood, the two halves of both DS2 and DS3 moved apart during the brazing cycle to create a wedge-shaped gap in the bond plane. At the forward end of each sample it was about 0.25mm (.010in) wide as shown in the two views of Fig. 12d. At the trailing edge there was, however, virtually no gap and a relatively good bond was formed.

Both samples had therefore failed to achieve an adequate brazed joint and there was excessive cross leaking between channels. From a production viewpoint, such samples would be useless but at this early stage in a research and development project it was considered worthwhile proceeding to cut suitable airfoil contours on the top and bottom surfaces of both samples to see what other problems might be encountered. Fig. 13a shows sample DS2/MG13 after wire-cutting to create segment 5M, together with offcuts from the top and bottom surfaces. Prior to profiling the upper and lower surfaces, 10mm (0.4in) wide strips were cut from each side of both DS2/MG13 and DS3/MG14 in such a way that, after a further grinding stage, a section through both a channel and pressure orifice was obtained. One such section is shown in Fig. 13b at a magnification of X15. The dark line running along the center of the

channel is the unbonded gap and the black dashed line intersecting the 0.37mm (.015in) diameter drilled hole is meant to represent where the airfoil surface would have been created. The other feature noticeable is the partial blockage of the 1mm (.040in) diameter pilot hole by braze alloy. In a well-fixtured braze such blockage is much less likely to occur, as capillary action would draw the braze alloy into the much narrower gap between the two surfaces.

The bond formed at the trailing edge was of a much higher quality and the channel that was to outcrop at the trailing edge was unblocked, as can be seen at the left of Fig. 13c at a magnification of X15. The right hand view in Fig. 13c shows part of the 0.05mm (.002in) nickel shim at the extreme right hand side of the trailing edge. Fig. 13d shows two views, at X15 (upper) and X3 (lower), of the trailing edge orifice after the airfoil surfaces had been EDM wire-cut on to this segment.

The final views in Figs. 14a to d show the appearance of the upper and lower surfaces of segments 5M and 6M in the as-wirecut condition. The orifices in both segments had been pre-drilled in such a way as to have orifices at 1% intervals from 99% to 82% of the airfoil, supposing it to have a 325mm (13in) chord. In segment 5M (DS2) the orifices were arranged in staggered rows such that alternate rows outcropped on the upper and lower surfaces on the right hand side of the central orifice on the trailing edge, while the orifices on the left hand side outcropped to fill in the missing positions. Thus, for example, if the underside of segment 5M is viewed from the trailing edge, as in Fig. 14a, the 99, 98, 97 and 96% orifices would be found on the left of the central orifice, while the 95, 94, 93, 92 and 91% orifices are on the right. 90, 89, 88, 87 and 86% (86 was sectioned in the offcut) are then found on the left of the central orifice and 85, 84, 83 and 82% are on the right.

Another feature noticeable in Fig. 14a, particularly with the 84, 83, and 82% orifices at the top right of the picture, is the larger diameter of some of the orifices. This is best understood by first reconsidering Fig. 13b which shows a 1mm (.040in.) pilot hole drilled from the channel towards the plate surface, with a 0.37mm (.015in.) hole outcropping at the surface. Remembering also that, because of the fixturing problem discussed earlier, the gap between the two plates DS2A and DS2B tapered from about 0.05mm (.002in.) at the trailing edge to about 0.3mm (.012in.) at the forward end. It can thus be appreciated that the profiled surface actually cut by the EDM wire machine was at a different position from that calculated when the 1mm (.040in.) pilot holes were drilled, and that in some cases the wire cut through the 1mm (.040in.) pilot hole instead of the intended 0.37mm (.015in.) orifice.

The upper surface of segment 5M is shown in Fig. 14b, and it also shows rows of orifices outcropping alternately on either side of the center line, as well as the 1mm (.040in.) pilot holes cut through due to the excessive thickness of the bond line. (When comparing Figs. 14a and b, it should be remembered that any feature apparently on the left hand side of the airfoil centerline on the lower surface in Fig. 14a, would occur at the corresponding mirror image position on the right hand side of the centerline on the upper surface in Fig. 14b.)

A different set of orifice positions were drilled into the two plates, DS3A and DS3B, that eventually formed segment 6M. In this case all the orifices on the upper surface were on the right hand side of the central trailing edge orifice, as viewed from the trailing edge, while all the orifices on the lower surface were on the left of the centerline. Thus, the orifices visible in Fig. 14c, are those on the upper surface of the airfoil, which appears on the right in Fig. 14c. Also shown, on the left of Fig. 14c, is the offcut formed when the upper profile was EDM wire-cut. This illustrates a further problem to be considered and overcome before such segments can be produced reliably, namely the need to ensure that the work piece is set up with the line of symmetry along its bond plane aligned completely parallel to the wire axis. If this is not ensured, tapered sections and incorrectly located orifices will be the result.

Finally, Fig. 14d shows a closer view of the orifices on the lower surface of segment 6M, which, it should be remembered, lie to the left of the center line. The view on the right is of the lower surface itself, and out of the 13 orifices visible, 12 have the desired size of 0.37mm (.015in.) and only in one case has the 1mm (.040in.) pilot hole been cut through instead. Comparison with the view of the offcut (shown on the left in Fig. 14d) which only has 0.37mm (.015in.) holes visible, infers that the pilot hole had been cut through within 0.37mm (.015in.) of the intended orifice level, as this was the thickness of the wire used in the EDM wire-cut machine. In fact, of the 17 orifices formed on the lower surface, only 3 were 1mm (.040in.) in diameter.

Thus, due to the fixturing problems that led to the creation of a wedge shaped gap in the bond plane, segments 5M and 6M did not achieve the target of producing segments with pressure-tight, unblocked channels that connected to a total of 39 orifices located at 1% intervals on both upper and lower airfoil surfaces and in the trailing edge. There was, therefore, no attempt made to cryocycle these components, as the results would not have had much significance. However, the progress made up the technological learning curve by the fabrication of these components, suggests that the achievement of the initial objectives are significantly closer to realization.

CONCLUSIONS

As will by now be apparent to a reader who has digested the main text of this report, many of the technical objectives set out at the beginning have been realized during the period of performance of Phase 1. Furthermore, it has also proved possible to combine many of them to allow fabrication of realistic trailing edge segments of a thin supercritical airfoil. The major achievements may be summarized as follows;

- EDM wire-cutting- : This has been shown to be a cost-effective technique of cutting profiled bond planes and airfoil contours into 300 series stainless steels and Vascomax 200. There is also good reason to believe that it would be equally satisfactory for superalloys and other relevant materials. Complex profiles need to be cut separately on each face if they are to fit exactly, the co-ordinates being set-up on each side of the EDM wire. To minimize the amount of finishing required, as many co-ordinates as possible should be used to define the profile: enough material also needs to be left outside the finished dimensions to allow for the removal of blemishes created by the wire cutting through electrical discontinuities such as pressure orifices.

- Chemical milling - : This has been shown to be a highly cost-effective technique for creating a complex network of channels in the surface of 300 series stainless steels and Vascomax 200. It has also proved possible to create matched pairs of channels on both the concave and convex surfaces of profiled bond planes. A particular advantage is the ability to carry out corrective work at the intermediate stages. Furthermore, drilled orifice holes can be accurately and conveniently located at the channel ends. A simple extension of the technique could allow the formation of channels with variations in their width and depth.

- Vacuum brazing - : Bonded joints have been formed using MBF 20 in A286, Nitronic 40, Hastalloy X, Vascomax 200 and type 321 stainless steel. Reasonable success was achieved with small, flat plate samples. Scale up to large samples presents difficulties due to warpage created by the thermal relief of residual stresses. Limited success has been achieved with brazing profiled bond planes, but further work on fixturing, the use of stop-offs and control of dimensional instability will be necessary before vacuum brazing can become a routine, cost-effective fabrication technique.

- Metallurgy of Vascomax 200 - : Brazing at temperatures in excess of 1000C (1830F) causes excessive grain growth in 18 nickel maraging steels, thus precluding the use of MBF 20. Evaluation of four other brazing alloys led to the selection of a nickel-palladium alloy, MBF 1005, for use with Vascomax 200. Its metallurgical structure appears satisfactory, but further tests will be needed to measure the strength of the bonds.

-Orifice exposure - : High quality orifices have been produced by the technique of pre-drilling blind holes from the ends of the chemically-milled channels, such that they subsequently outcrop in the airfoil surface when its profile is EDM wire-cut.

-Joining segments - : One possible design of joining trailing edge segments to the main airfoil has been investigated from a mechanical viewpoint. Pressure channels were not, however, joined and the experience gained from this initial configuration would be used to design an improved version for use in a real airfoil.

Thus Phase 1 of the PITACT program has developed a range of technologies and combined them to allow the fabrication of three segments of a 6% thick supercritical airfoil which were heavily instrumented with orifices. Cross-leaks due to bonding difficulties were present in these segments, but success in other samples leads to high confidence in that this problem will be resolved.

-TECHNICAL FEASIBILITY OF FUTURE WORK

From the progress made during Phase 1 of the PITACT program, it can reasonably be concluded that fabrication of segments of supercritical airfoils having thicknesses of about 6% chord, with pressure orifices at 1% stations from about 80% to 100% chord, is highly feasible. Indeed, two such segments would have been fabricated in Phase I, ahead of schedule, if the fixturing problems had not arisen with samples DS2 and DS3.

Detailed proposals for Phase 2 of the PITACT program are to be made in our response to IFB/RFP Number 1-06-0100.0630. In general terms, however, the proposed Phase II technical objectives will aim at the construction of a 2D airfoil to be testable in the LaRC 0.3-m TCT. The configuration of the airfoil will be such as to have a basic airfoil onto which interchangeable leading and trailing edges with a high density of pressure orifices can be mounted. Such a project would be technically feasible within the two year time span of Phase II. Its design would require the active assistance of LaRC engineers in order to ensure that the airfoil configuration was of a type generally needed for aerodynamic research, and not just a sterile exercise in technical development.

Table 1 Summary of results from PITACT Samples

Sample Ident.	Material Type	Characteristics of Finish	Channel	Bonding surface w d @sp (mm)	Hole(mm)	Combinat Ident.
DEI 1A	A286	Ground	E.D.M.	.25x.25 @ 5	.5	MG1
DEI 1B	"	"	------	-----------	.5	MG1
DEI 1C	"	"	------	-----------	--	---
DEI 2A	Nitronic	Ground	E.D.M.	.25x.25 @ 5	.5	MG2*
DEI 2B	40	"	------	-----------	.5	MG3*
DEI 2C	"	"	------	-----------	--	---
DEI 3A	Hastalloy	Ground	E.D.M.	.25x.25 @ 5	.5	MG3*
DEI 3B	"	"	------	-----------	.5	MG2*
DEI 3C	"	"	------	-----------	--	---
DEI 4A	Vascomax	Ground	E.D.M.	.25x.25 @ 5	.5	MG4
DEI 4B	200	"	------	-----------	.5	MG4
DEI 4C	"	"	------	-----------	--	---
DEI 5A	321 SS	Ground	E.D.M.	.25x.25 @ 5	.5	MG5
DEI 5B	"	"	------	-----------	.5	MG5
DEI 5C	"	"	------	-----------	--	---
LJS 1	316 SS	Lapped	Slit saw	.5 x.5 @ 4	--	MG6
LJS 2	316 SS	"	"	"	--	MG6
RH 1	304 SS	"	Chem-mill	.6 x.25 @ 2.45	1,.5,.32	MG6
RH 2	304 SS	Lapped	Chem-mill	.6 x.25 @ 2.45	1,.5,.32	MG7
LJS 3	304 SS	"	--------	--------------	--	MG7
RH 3	Vasco200	Lapped	Chem-mill	letters	--	n/a
DS 1A	304 SS	EDM wire	Chem-mill	.4 x.25 @ 3	1,.5,.32	MG8
DS 1B	"	"	--------	-------------	--	MG8
RH 5a,b	Vasco200	Lapped	Chem-mill	.5 x.3 @ 2.45	--	MG9
RH 6a,b	"	"	"	"	--	MG10
RH 7a,b	"	"	"	"	--	MG11
RH 8a,b	"	"	"	"	--	MG12
DS 2A	Vasco200	EDM wire	Chem-mill	.7 x.35 @ 3	1 & .37	MG13
DS 2B	"	"	"	"	"	MG13
DS 3A	Vasco200	EDM wire	Chem-mill	.7 x.35 @ 3	1 & .37	MG14
DS 3B	"	"	"	"	"	MG14

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(Table 1 CONT)

Combination Ident.	Braze	Effect of Channel	Holes	Braze on; Bond	G.Size	Comments
MG1	MBF 20	open	n/a	good	OK	wedge
MG1						
---	-----	-----	----	----	--	control
MG2*	MBF 20	open	n/a	good	OK	*Nitronic
MG3*						/Hastalloy
---	-----	-----	----	----	--	control
MG3*	MBF 20	open	n/a	good	OK	*Hastalloy
MG2*						/Nitronic
---	-----	-----	----	----	--	control
MG4	MBF 20	blocked	closed	good	large	grain
MG4						growth
---	-----	-----	----	----	--	control
MG5	MBF 20	open	OK	good	OK	Segment
MG5						2M
---	-----	-----	----	----	--	control
MG6	MBF 20	partly	n/a	good	OK	Segment
MG6		blocked	n/a			3F
MG6		open	OK	good	OK	Triplet
MG7	MBF 20	open	OK	good	OK	Segment
MG7						3M
n/a	n/a	n/a	n/a	n/a	n/a	Chem Test
MG8	MBF 20	cross-	open	good	OK	Segment
MG8		leak				4M
MG9	MBF 1002	blocked	n/a	2phase	OK?	1010C (1850F)
MG10	MBF 1005	"	"	2phase	OK	927C (1700F)
MG11	MBF 65A	"	"	2phase	OK	982C (1800F)
MG12	MBF 20Md	"	"	good	OK?	1010C (1850F)
MG13	MBF 1005	cross-	open/	good	OK	Segment 5M
MG13	927C	leak	closed			927C (1700F)
MG14	BBF 1005	cross-	open/	good	OK	Segment 6M
MG14	965C	leak	closed			965C (1770F)

APPENDICES 1 & 2

Table A2 — Details of PITACT Samples — A286V200

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin:	A286 Dynamic Engineering Inc.		
Identification :	DEI 1A	DEI 1B	DEI 1C
Size and Shape :	DEI 1A,B,&C;50x50x6 mm rectangular plates		
Faying Surface :	DEI 1A,B,&C;Ground to better than 500 micro in.		
Channels :	w=.25,d=.25,spaced @ 5mm	none	none
Holes :	4 each .5mm dia, 2mm deep.	as DEI 1A	none
Comment :	Channels EDM machined to Drawing 1		control

BRAZING CYCLE

Combination Ident:	DEI 1A + 1B = MG1	n/a
Braze alloy :	MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)	n/a
Fixture :	2 each 3.7mm dowels + weight	n/a
Furnace Schedule :	RT-1065C in 30 min,15 min hold, slow cool	n/a
Comment :	Possible loss of vacuum as samples discolored;	
" :	Dowels seized, wedge shaped gap;bond at one end.	

METALLURGICAL EXAMINATION

Channels :	Clear at brazed end	n/a
Holes :	n/a	n/a
Aggression :	None	n/a
Grain Structure :	OK	control
Comment :	Sample proves A286 brazable using MBF20.	
" :	No further use as segment.	

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin:	Vascomax 200 Dynamic Engineering Inc.		
Identification :	DEI 4A	DEI 4B	DEI 4C
Size and Shape :	DEI 4A,B,&C;50x50x6 mm rectangular plates		
Faying Surface :	DEI 4A,B,&C;Ground to better than 500 micro in.		
Channels :	w=.25,d=.25,spaced @ 5mm	none	none
Holes :	4 each .5mm dia, 2mm deep.	as DEI 4A	none
Comment :	Channels EDM machined to Drawing 1		control

BRAZING CYCLE

Combination Ident:	DEI 4A + 4B = MG4	n/a
Braze alloy :	MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)	n/a
Fixture :	2 each 3.7mm dowels + weight	n/a
Furnace Schedule :	RT-1065C in 30min,15 min hold,slow cool	n/a
Comment :	Fully Bonded	
" :		

METALLURGICAL EXAMINATION

Channels :	Blocked	n/a
Holes :	Mainly blocked	n/a
Aggression :	None	n/a
Grain Structure :	Excessive grain growth as T braze 1000C.	control
Comment :	Toughness @ 77K would be lowered.	
" :	No further use as segment.	

Table A3 — Details of PITACT Samples — a:nithast

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin	Nitronic 40	Dynamic Engineering Inc.	
Identification	DEI 2A	DEI 2B	DEI 2C
Size and Shape	DEI 2A,B,&C;50x50x6 mm rectangular plates		
Faying Surface	DEI 2A,B,&C;Ground to better than 500 micro in.		
Channels	w=.25,d=.25,spaced @ 5mm	none	none
Holes	4 each .5mm dia 2mm deep.	as DEI 2A	none
Comment	Channels EDM machined to Drawing 1		control

BRAZING CYCLE

Combination Ident	DEI 2A + 2B = MG2*	n/a
Braze alloy	MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)	n/a
Fixture	2 each 3.7mm dowels + weight	n/a
Furnace Schedule	RT-1065C in 30 min, 15 min hold, slow cool	n/a
Comment	*Samples mixed up at Metglas, Nitronic 40 matched	
"	with Hastalloy X.	

METALLURGICAL EXAMINATION

Channels	Clear at brazed end	n/a
Holes	n/a	n/a
Aggression	None	n/a
Grain Structure	OK	control
Comment	Good bond formed when surfaces kept close together	
"	No further use as segment	

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin	Hastalloy X	Dynamic Engineering Inc.	
Identification	DEI 3A	DEI 3B	DEI 3C
Size and Shape	DEI 3A,B,&C;50x50x6 mm rectangular plates		
Faying Surface	DEI 3A,B,&C;Ground to better than 500 micro in.		
Channels	w=.25,d=.25,spaced @ 5mm	none	none
Holes	4 each .5mm dia 2mm deep.	as DEI 3A	none
Comment	RT-1065C in 30min,15 min hold,slow cool		control

BRAZING CYCLE

Combination Ident	DEI 3A + 3B = MG3*	n/a
Braze alloy	MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)	n/a
Fixture	2 each 3.7mm dowels + weight	n/a
Furnace Schedule	RT-1065C in 30 min, 15min hold, slow cool	n/a
Comment	*Samples mixed up at Metglas, Nitronic 40 matched	
"	with Hastalloy X.	

METALLURGICAL EXAMINATION

Channels	Clear at brazed end	n/a
Holes	n/a	n/a
Aggression	None	n/a
Grain Structure	OK	control
Comment	Good bond formed when surfaces kept close together	
"	No further use as segment	

Table A4	Details of PITACT Samples & Segments	stain321

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin:	321 Stainless Dynamic Engineering Inc.		
Identification :	DEI 5A	DEI 5B	DEI 5C
Size and Shape :	DEI 5A,B,&C;50x50x6 mm rectangular plates		
Faying Surface :	DEI 5A,B,&C;Ground to better than 500 micro in.		
Channels :	w=.25,d=.25,spaced @ 5mm	none	none
Holes :	4 each .5mm dia 2mm deep.	as DEI 5A	none
Comment :	Channels EDM machined to Drawing 1		control

BRAZING CYCLE

Combination Ident:	DEI 5A + 5B = MG5	n/a
Braze alloy :	MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)	n/a
Fixture :	2 each 3.7mm dowels, weight + Nickel foil	n/a
Furnace Schedule :	RT-1065C in 30 min, 15 min hold, slow cool	n/a
Comment :	Sample brazed later than DEI 1 to 4,.05 mm Nickel	
" :	shim used as spacer with .04 mm braze alloy	

METALLURGICAL EXAMINATION

Channels :	Clear	n/a
Holes :	Clear	n/a
Aggression :	None	n/a
Grain Structure :	OK	control
Comment :	Only sample from DEI series successfully brazed	
" :		

SEGMENT IDENTIFIER 2M

SURFACE PROFILE

Upper contour :	Planar
Upper finish :	Ground
Lower contour :	n/a
Lower finish :	n/a
Comment :	Unblocked pressure orifices exposed on upper
"	surface

JOINT CONFIGURATION

Male/female :	Male
Detail :	
Comment :	
" :	

CONCLUSIONS

Sample showed nickel shim to be effective as spacer in keeping bond to required thickness and preventing channel blockage. Pressure orifices exposed by grinding upper contour showed good definition.

Table A5 Details of PITACT Samples & Segments rh21js3

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin:	304 Stainless, Southampton University,		
Identification	:	RH2 1	LJS3
Size and Shape	:	Both 80 x 60 x 6mm, rectangular	
Faying Surface	:	Both lapped	
Channels	:	Chem Milled,w=.25,d=.6mm,spaced @ 2.45mm	none
Holes	:	1, .5 & .32mm	none
Comment	:	details of RH2 as to Drawing 2	
"	:		

BRAZING CYCLE

Combination Ident:		RH2 + LJS3 =MG7
Braze alloy	:	MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)
Fixture	:	2 each 2mm dowels, weight + Nickel foil
Furnace Schedule	:	RT-1065C in 30 min, 30 min hold, slow cool
Comment	:	Chem milled channels extended to edge of
"	:	RH2 using .5mm wide saw slit to depth .5mm

METALLURGICAL EXAMINATION

Channels	:	Clear
Holes	:	Clear
Aggression	:	None
Grain Structure	:	OK
Comment	:	Perfect braze,no voids,no blockages.
"	:	

SEGMENT IDENTIFIER 3M

SURFACE PROFILE

Upper contour	:	3 separate planes at increasingly steep angles
Upper finish	:	EDM wire cut,hand ground & diamond polished
Lower contour	:	n/a
Lower finish	:	n/a
Comment	:	3 planes chosen to intersect pre-drilled
"	:	holes & form orifices; aft plane gives
	:	taper section through bond plane.

JOINT CONFIGURATION

Male/female	:	Male
Detail	:	Drilled holes for tube insertion
"	:	
Comment	:	All channels open,no cross leaks:taper
	:	section showed void-free bond line. Holes
	:	have good definition.

CONCLUSIONS

Successful segment confirming validity of concept of preforming half channels and drilling blind holes. Planar bond surface easier to prepare and quality control than profiled surfaces.

Table A6 Details of PITACT Samples & Segments

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin	316 Stainless,	Southampton University	
Identification	LJS 1	LJS 2	RH1
Size and Shape	All 80 x 60 x 6mm, rectangular		
Faying Surface	All lapped		
Channels	Slit sawn,w=.5mm,d=.5mm,spaced @ 2.45mm		*Chem mill
Holes	none	none	1,.5,.32mm
Comment	LJS1&2 to Drawing 3;RH1 to Drawing 2: *Chemically		
"	milled channels d=.6,w=.25,spaced @ 2.45mm		

BRAZING CYCLE

Combination Ident	LJS1 + LJS2 + RH1 =MG6
Braze alloy	MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)
Fixture	2 each 2mm dowels, + weight + Nickel foil
Furnace Schedule	RT-1065C in 30 min, 15 min hold, slow cool
Comment	LJS1 & 2 had distorted during machining; further
"	warpage during braze gave thicker bond at edges.

METALLURGICAL EXAMINATION

Channels	LJS1/2 part blocked:	LJS2/RH1 open
Holes	n/a	open
Aggression	None	none
Grain Structure	OK	OK
Comment	Channels blocked at center of LJS1/2 due to warpage	
"	of plates during brazing	

SEGMENT IDENTIFIER 3F

SURFACE PROFILE

Upper contour	Planar
Upper finish	Ground
Lower contour	n/a
Lower finish	n/a
Comment	Upper profile ground to give continuous upper
"	surface when matched with segment 4M

JOINT CONFIGURATION

Male/female	Female
Detail	Groove 4mm wide x 12mm deep; docking ports
"	2mm square x 10mm long
Comment	Channels redrilled after brazing to clear blockage

CONCLUSIONS

Segment used to demonstrate proof-of-concept for joint configuration for possible use in fixing segment to main airfoil. Thin chordwise sections cut from segments 3F and 4M to show joint configuration.

Table A7 Details of PITACT Samples & Segments a:dslm4

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin:	304 Stainless, Southampton University,	
Identification :	DS1A	DS1B
Size and Shape :	Rectangular block 135x75x24mm (5x5x2.9in.)	
Faying Surface :	EDM wire-cut to co-ordinates in Drawing 5	as DS1A
Channels :	Chem Milled to pattern shown in Drawing 6	none
Holes :	1, .5 & .32mm drilled at channel ends	none
Comment :	Uneven chem-milled channels hand-finished	
" :	with needle file	

BRAZING CYCLE

Combination Ident: DS1A + DS1B = MG8
Braze alloy : MBF20 (AMS 4777B,Ni-7Cr-3Fe-4.5Si-3.2B)
Fixture : Edges of 2 halves laser-tacked while foil compressed
Furnace Schedule : RT-1037C in 30 min, 60 min hold, slow cool
Comment : Laser-tacking held gap at .08mm: but braze foil
" : 0.04mm thick thus unable to fill all gap

METALLURGICAL EXAMINATION

Channels : Clear
Holes : Clear
Aggression : None
Grain Structure : Some grain boundary sensitization away from bond.
Comment : Over-wide gap caused cross-leaks between some
" : channels especially at joint end.

SEGMENT IDENTIFIER 4M

SURFACE PROFILE

Upper contour : Wire EDM cut to co-ordinates in Drawing 5
Upper finish : EDM wire cut,hand polished with 600 grade abrasive
Lower contour : As upper contour
Lower finish : As upper finish
Comment : Pre-drilled holes in lower surface exposed by wire-
" : cutting giving clean orifice profile
:

JOINT CONFIGURATION

Male/female : Male
Detail : 2mm square castellations at 4mm centers,length 8mm.
" : Male square section comb projecting from tongue 4mm
" : thick and 8mm long.
Comment : Presure tight joint to be made between comb teeth
: and docking ports using adhesive or solder

CONCLUSIONS

Chem-milled channels in segment 4 are at 3mm centers but cross-leaked & thus not pressure-tight. Segment 4M thus used to demonstrate concept of castellated comb & docking port system to match segment 3F which has channels at 4mm centers.

Table A8 Details of PITACT Samples & Segments a:vastest

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin:	Vascomax 200 , LaRC round bar, 75mm dia.			
Identification :	RH5a&b	RH6a&b	RH7a&b	RH8a&b
Size and Shape :	Thichness 12mm (0.5in.), irregular shape			
Faying Surface :	Lapped flat			
Channels :	Chem-Milled			
Holes :	none			
Comment :	-			
" :	-			

BRAZING CYCLE

Combination Ident:	MG9	MG10	MG11	MG12
Braze alloy :	MBF 1002	MBF 1005	MBF 65A	mod. MBF 20
Fixture :	0.59 Kg weight			
Furnace Temp. :	1010C (1850F)	927C (1700F)	982C(1800F)	1010C(1850F
Furnace schedule :	Heat to brazing temperature in 30 minutes , hold for			
" :	15 minutes, then furnace cool.			

METALLURGICAL EXAMINATION

Channels :	Blocked			
Holes :	None			
Aggression :	None?	none	slight	slight
Grain Structure :	Slight growth	OK	excessive	excessive
Comment :	Rejected	Chosen	Rejected	Rejected
" :				

SEGMENT IDENTIFIER n/a

SURFACE PROFILE

Upper contour :
Upper finish :
Lower contour :
Lower finish :
Comment :
" :
:

JOINT CONFIGURATION n/a

Male/female :
Detail :
" :
" :
Comment :
:

CONCLUSIONS

MBF 1005 alloy chosen for further brazing
Vascomax 200 samples

Table A9 Details of PITACT Samples & Segments a:ds2ds3

BASIC CHARACTERISTICS & INITIAL PREPARATION

Material & Origin:	Vascomax 200 , Vasco Teledyne	
Identification :	DS2	DS3
Size and Shape :	Rectangular, 120x70x11mm (4.8x2.8x0.44in.)	
Faying Surface :	EDM wire-cut as per Fig. 1 and Drawing 7	
Channels :	Chem-Milled as per Drawing 8 on both surfaces.	
Holes :	1 and 0.37mm (.040 and .015in.)	
Comment :	DS2 and DS3 have different orifice layouts	
"	DS2 has rows of orifices alternating on upper &	
"	lower airfoil surfaces to right and left of center	
"	line; DS3 has all upper orifices on right, lower,lef	

BRAZING CYCLE

Combination Ident:	MG13	MG14
Braze alloy :	MBF 1005	MBF 1005
Fixture :	1.15 Kg weight and dowel pins	
Furnace Temp. :	927C (1700F)	965C (1770
Furnace schedule :	Heat to brazing temperature in 20 minutes , hold for	
" :	15 minutes, then furnace cool.	

METALLURGICAL EXAMINATION

Channels :	Open, but with excessive cross-leaks
Holes :	Generally open
Aggression :	None
Grain Structure :	No growth
Comment :	Fixtures failed to prevent tapered gap of
" :	0.25mm (.010in.) at forward end of both segments

SEGMENT IDENTIFIER	5M	6M

SURFACE PROFILE

Upper contour :	EDM wire-cut to Fig.1c and Drawing 7
Upper finish :	EDM wire-cut
Lower contour :	EDM wire-cut to Fig.1c and Drawing 7
Lower finish :	EDM wire-cut
Comment :	Some 1mm (.040in.) pilot holes cut through instead
" :	of 0.37mm orifices due to bond gap
:	

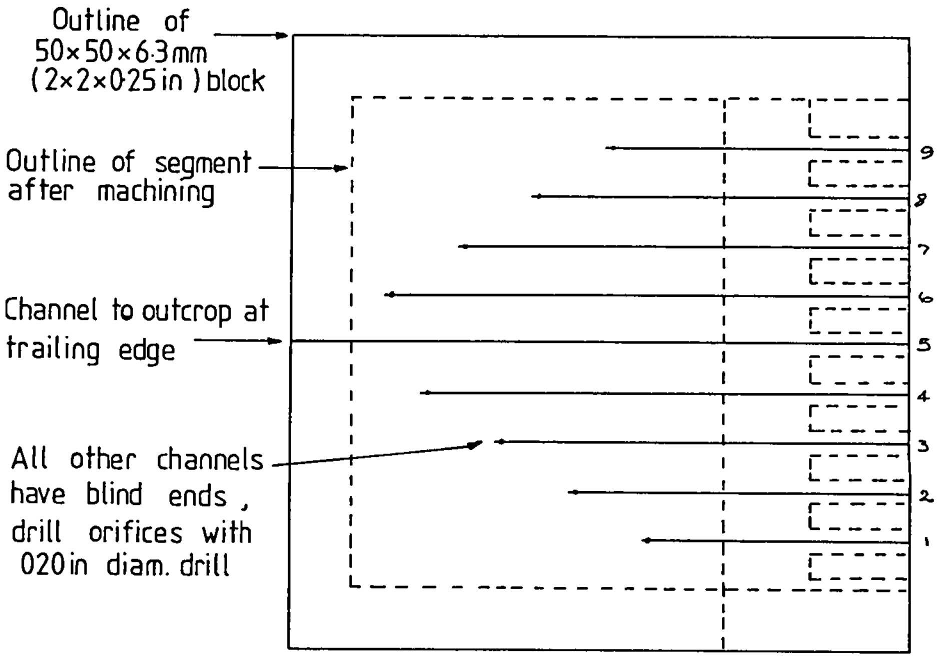
JOINT CONFIGURATION

Male/female :	none
Detail :	none
" :	
" :	
Comment :	Not fabricated because of channel cross-leaks
:	

CONCLUSIONS

Segments not pressure-tight due to failure of fixture during vacuum brazing. In all other respects the technologies worked.

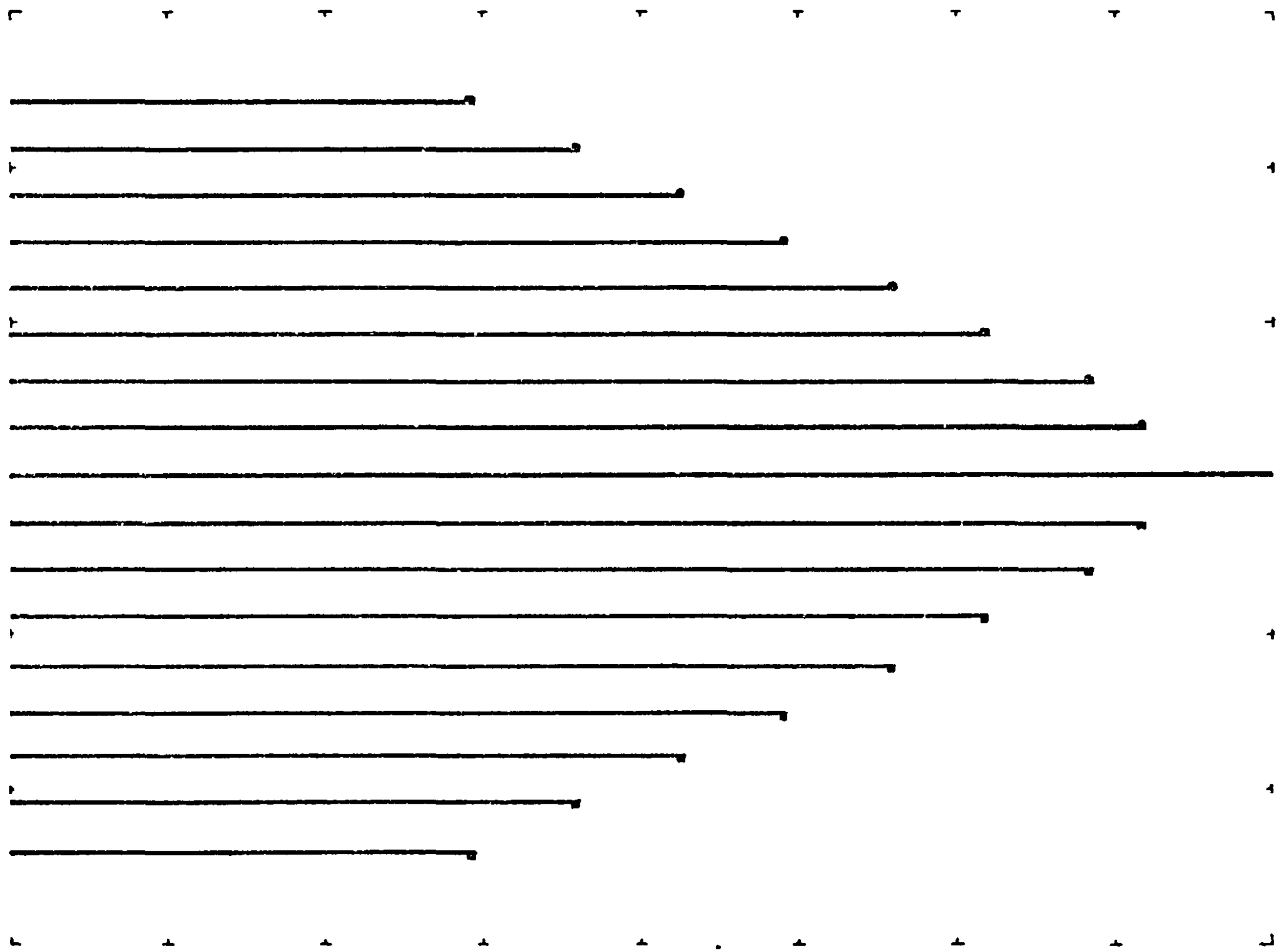
APPENDIX 2



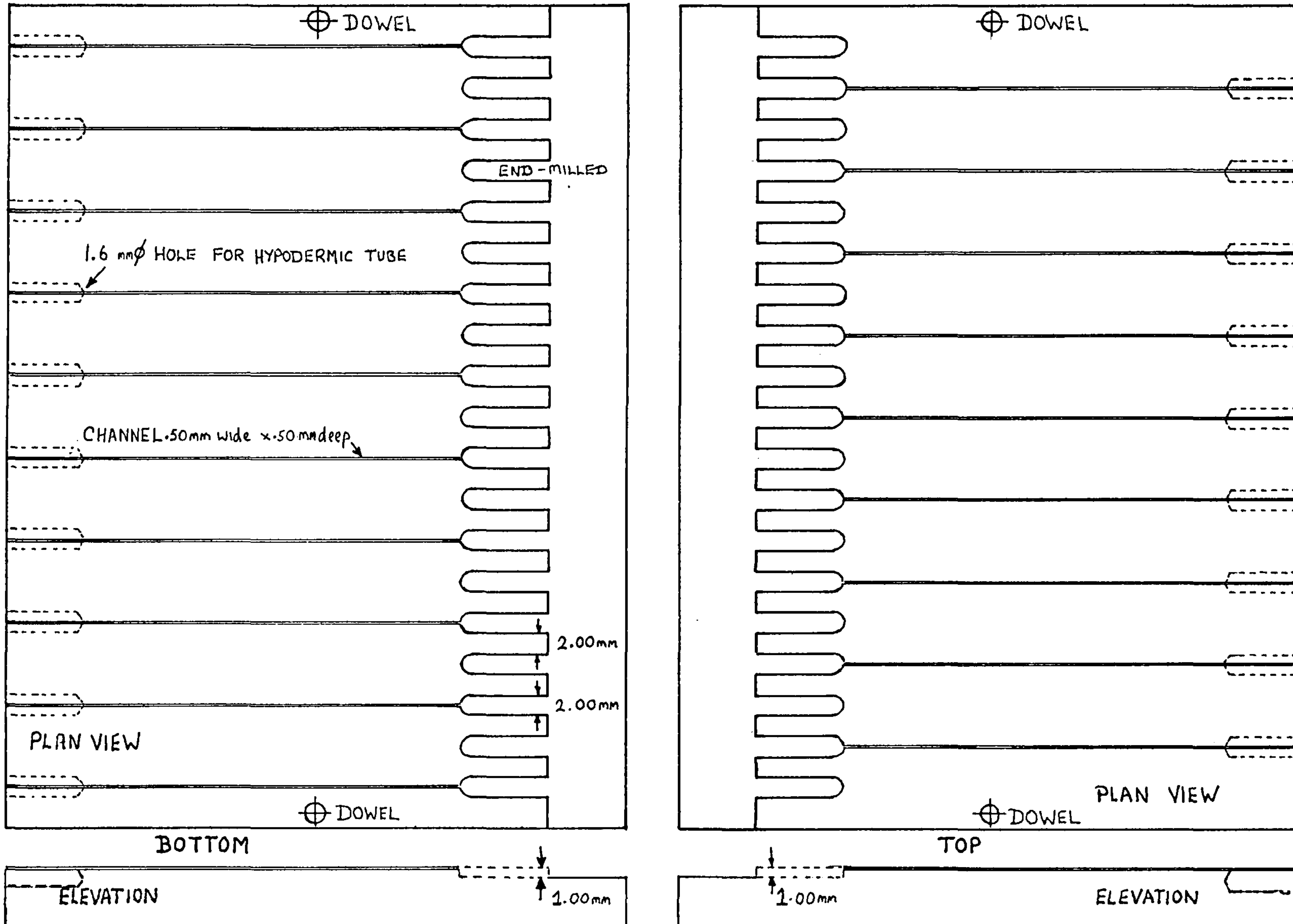
- Each segment has 2 blocks size 50×50×6·3mm. (2 × 2 × 0·25)
- Rough machine both blocks to size.
- Grind or lap one surface of each block flat to better than 500 μ inch.
- Machine network of channels into ground surface of one block
- Mark each block with material and segment identifiers
- Retain some scrap

Channel dimensions – ·010in wide
·010in deep

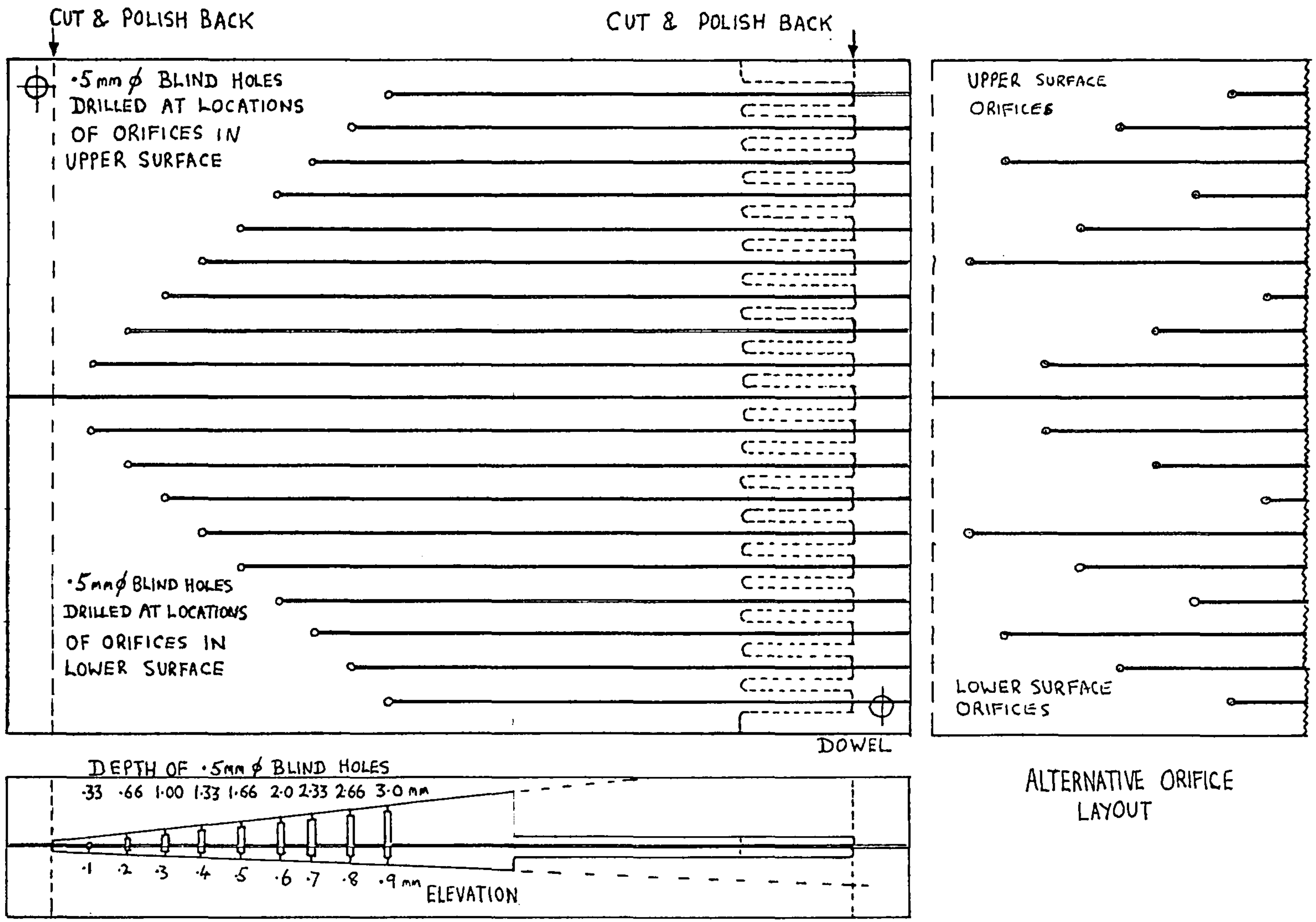
Materials. DEI 1 A 286 DEI 2 Nitronic 40 DEI 3 321 St. Steel DEI 4 18 Ni 200 grade DEI 5 Hastalloy	Scale : 2 × Full Size. Drawn by DAW. Date OCT 25, 1983.	Project : PITACT R&D. Drawing No. 1 Title : Simulated trailing edge segments for vacuum brazing tests.	APPENDIX 2 Drawing No. 1



A.C.& M.C. Inc Basin Road Industrial Center P.O. Box 705 New Castle De. 19720 Tel (302) 322 - 5411	Modifications N° Date Drawn by Original 16 Nov 83 DAW	Project: Pitact R&D Drawing: Channel layout for mask to be photographed & reduced for application to 80 x 60 mm stainless steel plate for chemical milling Scale 4 x Full Size (4 mm = 1 mm)	APPENDIX 2 Drawing No. 2



MATERIAL: 316 S.St. 80 x 60 x 6.25 mm	SCALE: 2 x FULL SIZE DRAWN BY: DAWigley DATE: Nov 21 1983	PROJECT: PITACT R&D TITLE: SIMULATED FEMALE JOINT SECTION, 2:2 RATIO	AC&MC Inc Basin Road Industrial Center PO Box 765 New Castle DE 19720 (302) 322-5411	APPENDIX 2 Drawing No. 3

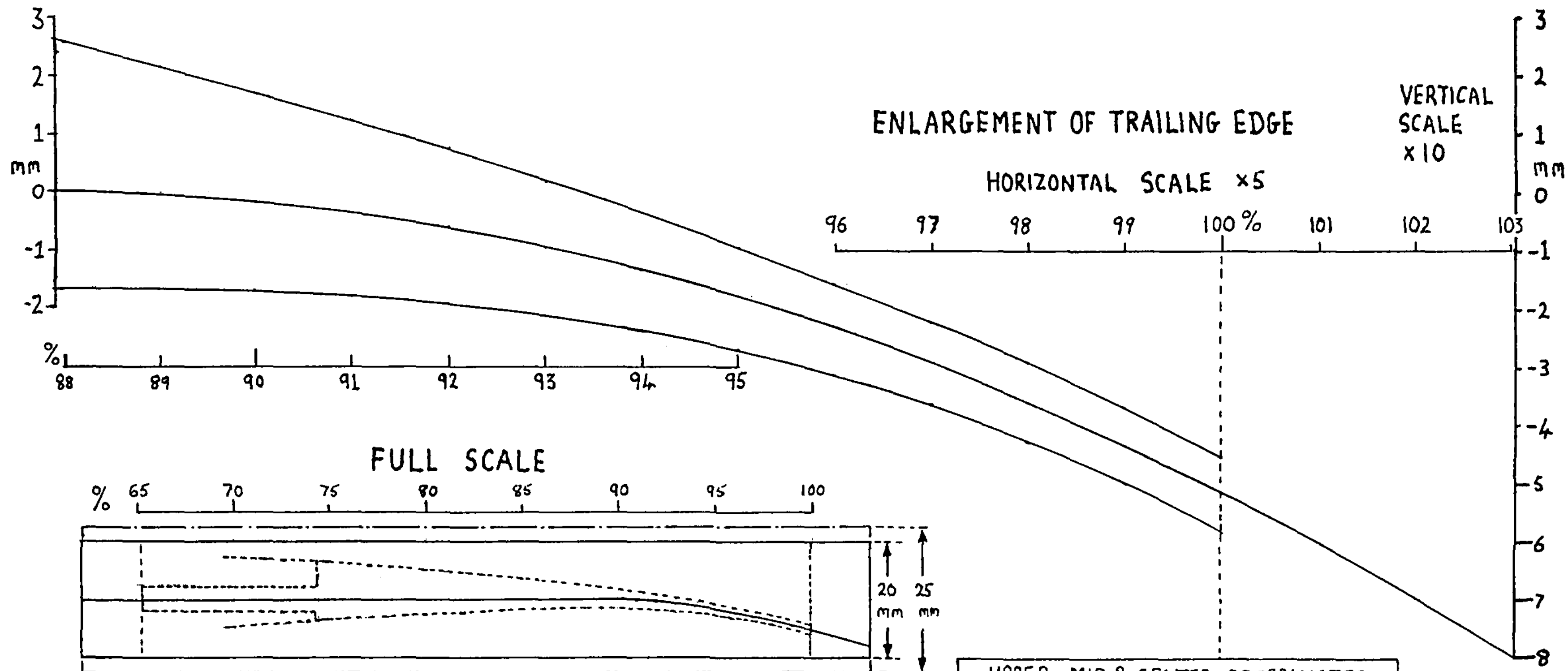


MATERIAL : 316 S. St. 80 x 60 x 6·25 mm	SCALE : 2 x FULL SIZE DRAWN BY : Dawyley DATE : Nov 22 1983	PROJECT: PITACT R&D TITLE: SIMULATED TRAILING EDGE, 2:1 RATIO, BLIND HOLES	AC&MC Inc. Basin Road Industrial Center PO Box 765, NewCastle, DE 19720	APPENDIX 2 Drawing No. 4

UPPER, MID & CENTER COORDINATES

mm 40 35 30 25 20 15 10 5 0 5 10

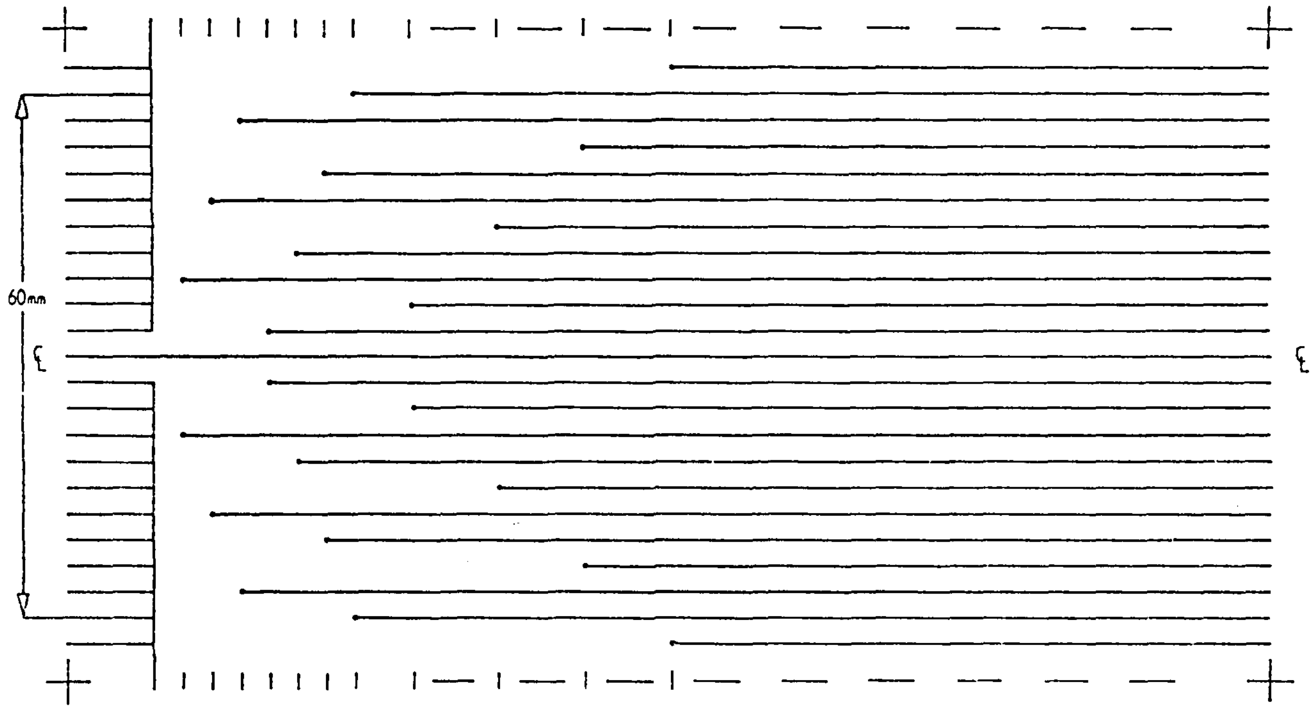
%	88	89	90	91	92	93	94	95	96	97	98	99	100 %	101	102	103 %
upper	2·541	2·112	1·683	1·221	+·726	+·198	-·363	-·957	-1·584	-2·244	-2·937	-3·696	-4·554			
mid	0	-·06	-·18	-·35	-·60	-·96	-1·36	-1·80	-2·34	-2·95	-3·61	-4·35	-5·19	-6·03	-6·96	-7·98
lower	-1·683	-1·683	-1·716	-1·782	-1·913	-2·112	-2·376	-2·706	-3·135	-3·663	-4·290	-5·016	-5·841			
mm	39·6	36·3	33·0	29·7	26·4	23·1	19·8	16·5	13·2	9·9	6·6	3·3	0	3·3	6·6	9·9



UPPER, MID & CENTER COORDINATES

%	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88
mm																								
upper						7·128	6·963	6·798	6·600	6·402	6·204	6·006	5·775	5·544	5·313	5.082	4·818	4·554	4·257	3·960	3·630	3.300	2·937	2·541
mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
lower (-ve)						4·884	4·653	4·422	4·191	3·960	3·729	3·498	3·267	3·069	2·871	2·673	2·475	2·310	2·145	2·013	1·881	1·782	1·716	1·683 (-ve)

MATERIAL: 304 S St 135 × 75 × 25 mm	SCALES: FULL & ENLARGED DRAWN BY: D.A. Wigley DATE: NOV 23 1983	PROJECT: PITACT R&D TITLE: PROFILE COORDINATES FOR WIRE E.D.M. CUTS.	A.C. & M.C. Inc Basin Road Industrial Center PO Box 765, New Castle, DE19720	APPENDIX 2 Drawing No. 5



A.C.&M.C. Inc.

Basin Road Industrial Centre,

P.O. Box 765 New Castle.

DE 19720

TEL (302) 322-5411

MODIFICATIONS.

No.	Date.	Drawn By.
Original	14 Dec 83	Z.A.W.

SCALE 2 × FULL SIZE (2mm = 1mm)

Project: PITACT R&D

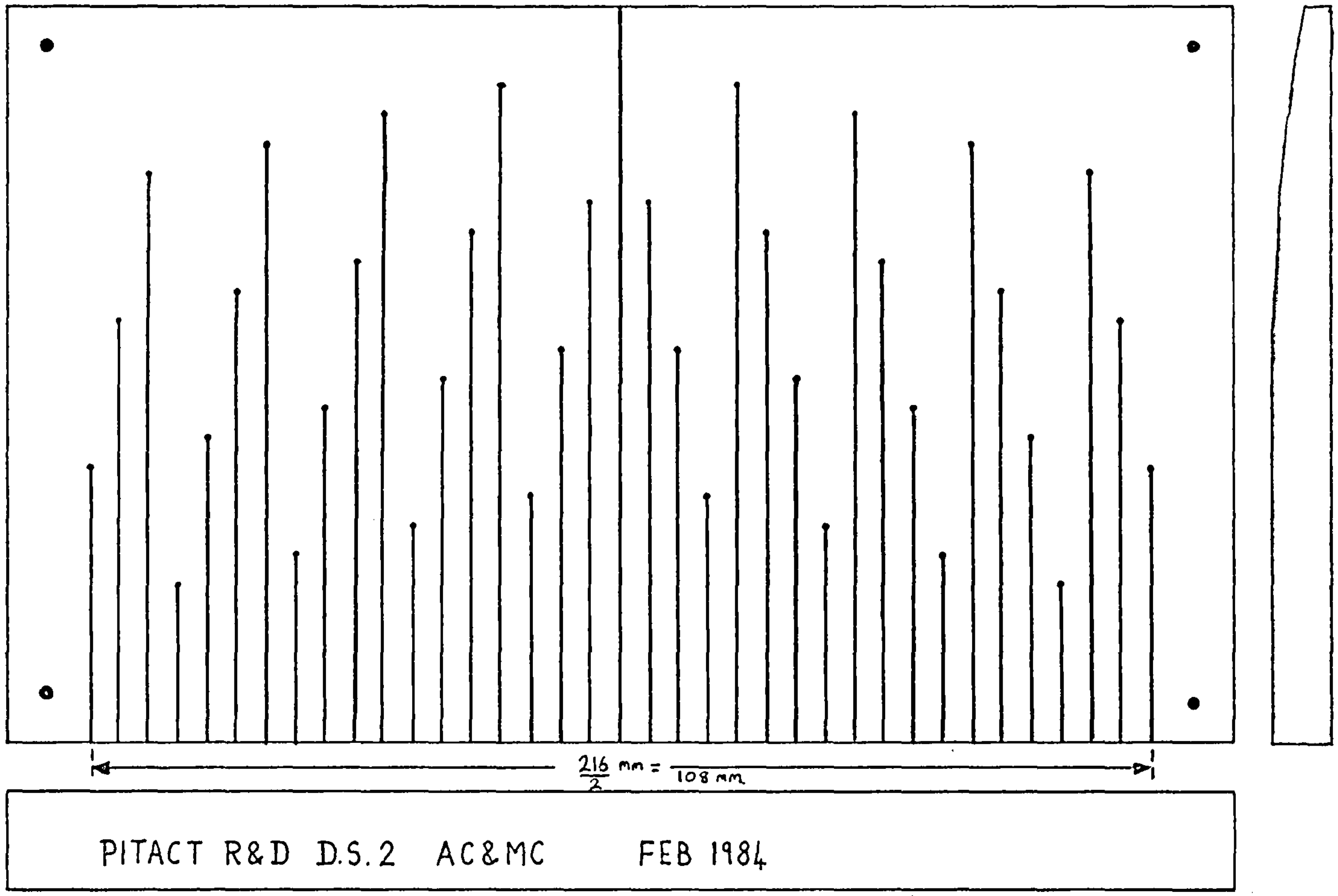
Drawing: Channel layout for mask to be photographed

No. 7. & reduced for application to 135 × 75 mm

Stainless Steel plate for chemical milling.

APPENDIX 2

Drawing No. 6



APPENDIX 2
Drawing No. 7

UPPER, MID & CENTER COORDINATES

mm 40 35 30 25 20 15 10 5 0 5 10

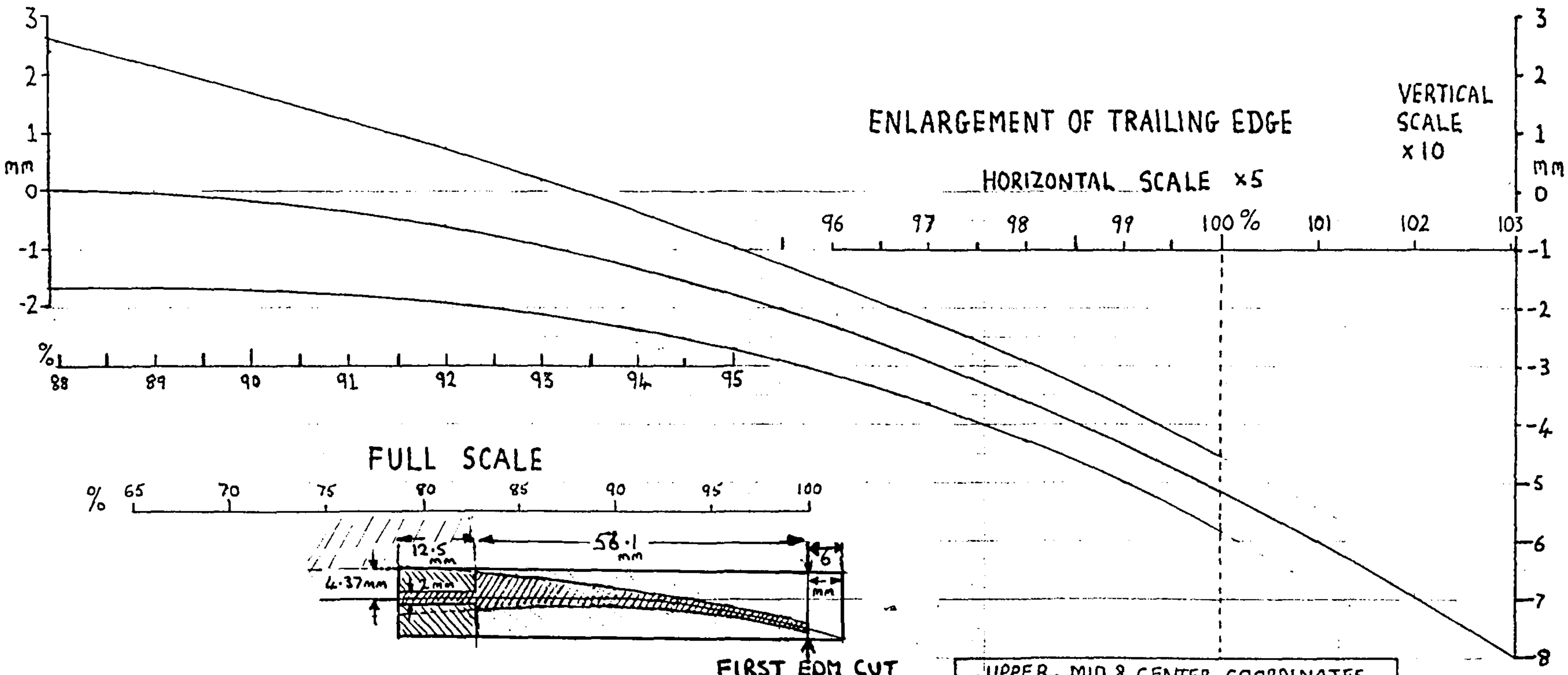
upper 2·541 2·352 ·112 1·92 1·683 1·451 ·221 ·95 +·726 ·65 +·198 −·1 −·363 −·65 −·957 1·25 −1·584 −1·9 −2·244 −2·6 −2·937 −3·3 −3·696 −4·1 −4·554 upper

mid 0 −·06 −·18 −·35 −·60 −·96 −1·36 −1·80 −2·34 −2·95 −3·61 −4·35 −5·19 −6·03 −6·96 −7·98 mid

lower −1·683 −1·683 −1·716 −1·782 −1·82 −1·913 −2·0 −2·112 −2·25 −2·376 −2·55 2·706 −2·9 −3·135 −3·4 −3·663 −4·0 −4·290 −4·6 −5·016 −5·35 −5·841 lower

mm 39·6 37·95 36·3 34·65 33·0 31·35 29·7 28·05 26·4 24·75 23·1 21·65 19·8 18·15 16·5 14·85 13·2 11·55 9·9 8·25 6·6 4·95 3·3 1·65 0 3·3 6·6 9·9 mm

% 88 89 90 91 92 93 94 95 96 97 98 99 100 % 101 102 103 %



UPPER, MID & CENTER COORDINATES

%	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88
mm																		59·4	56·1	52·8	49·5	46·2	42·9	39·6
upper						7·128	6·963	6·798	6·600	6·402	6·204	6·006	5·775	5·544	5·313	5·082	4·818	4·554	4·257	3·960	3·630	3·300	2·937	2·541
mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
lower (−ve)						4·884	4·653	4·422	4·191	3·960	3·729	3·498	3·267	3·069	2·871	2·673	2·475	2·310	2·145	2·013	1·881	1·782	1·716	1·683 (−ve)

MATERIAL: 304 S St 135 x 75 x 25 mm	SCALES: FULL & ENLARGED DRAWN BY: D Wigley DATE: NOV 23 1983	PROJECT: PITACT R&D TITLE: PROFILE COORDINATES FOR WIRE E.D.M. CUTS.	A.C. & M.C. Inc Basin Road Industrial Center PO Box 765, New Castle, DE19720	APPENDIX 2 Drawing No. 8

Fig. 1c Segments 5M & 6M

Fig. 1b Segment 4M

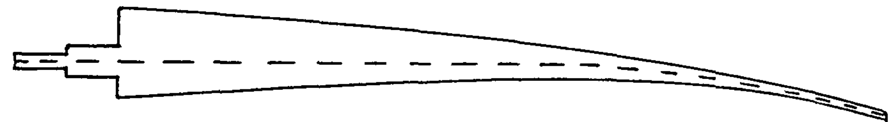


Fig. 1a

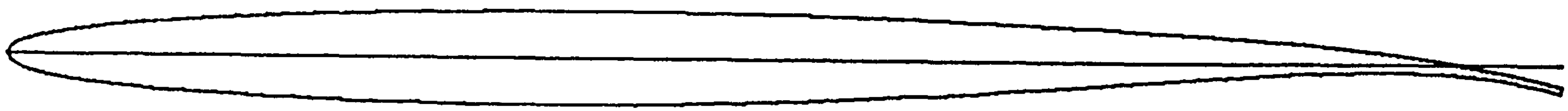


Fig. 1 SKETCH OF AIRFOIL 0631X7

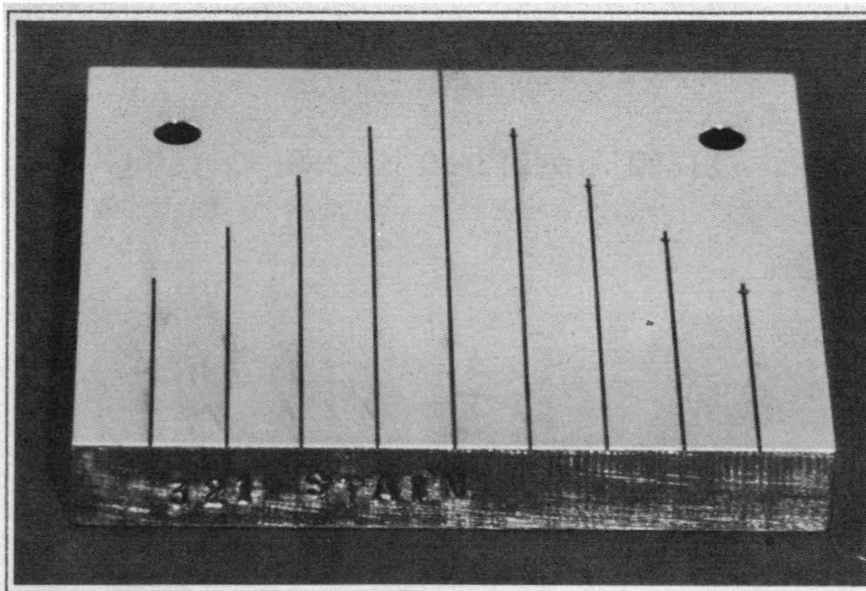


Fig. 2a Layout of spark-eroded channels and holes drilled in DEI A series plates

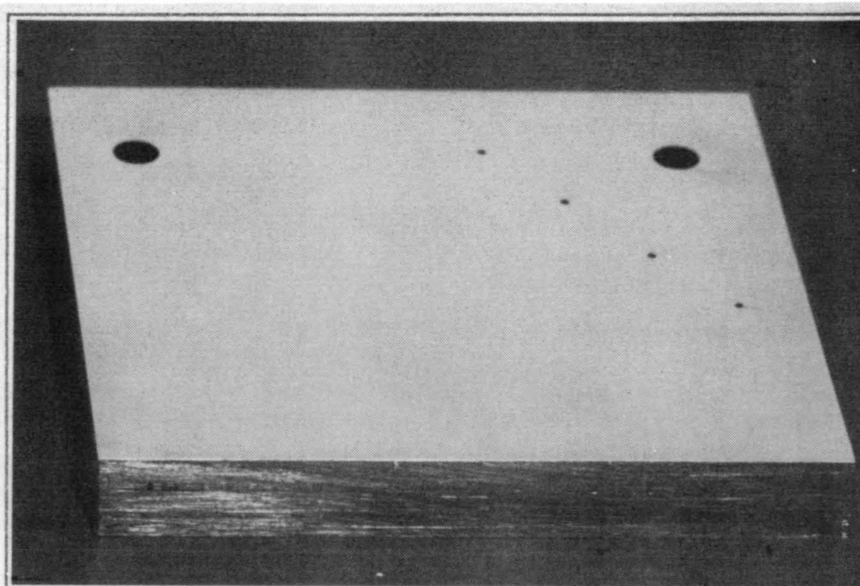
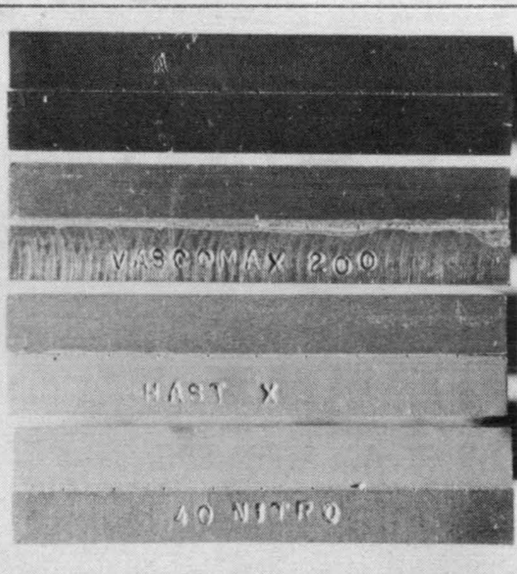
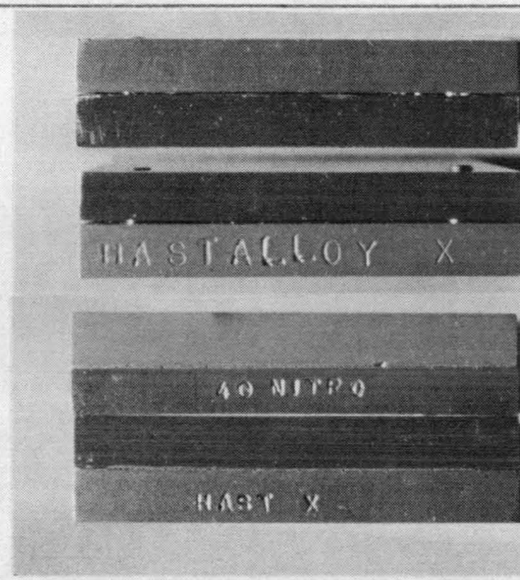


Fig. 2b Layout of holes drilled in DEI B series plates





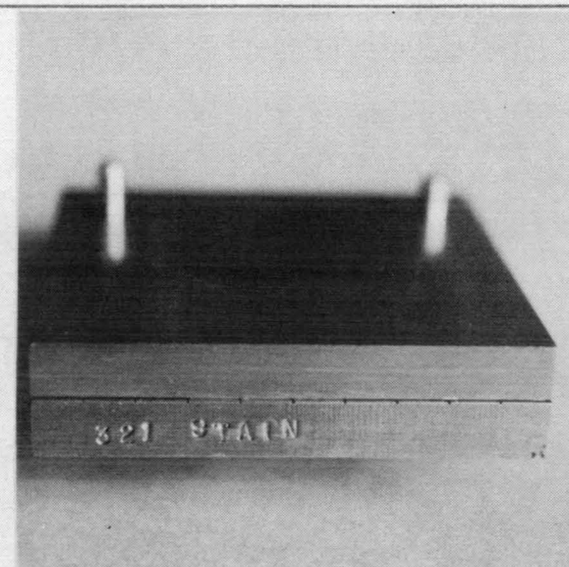


Fig. 2c(left) Brazed bonds in A286, Vascomax 200, Hastalloy X and Nitronic 40. Fig. 2d(center) Hastalloy X/Nitronic 40; top, unbonded: bottom, warped. Fig. 2e(right) DEI 5, 321 Stainless

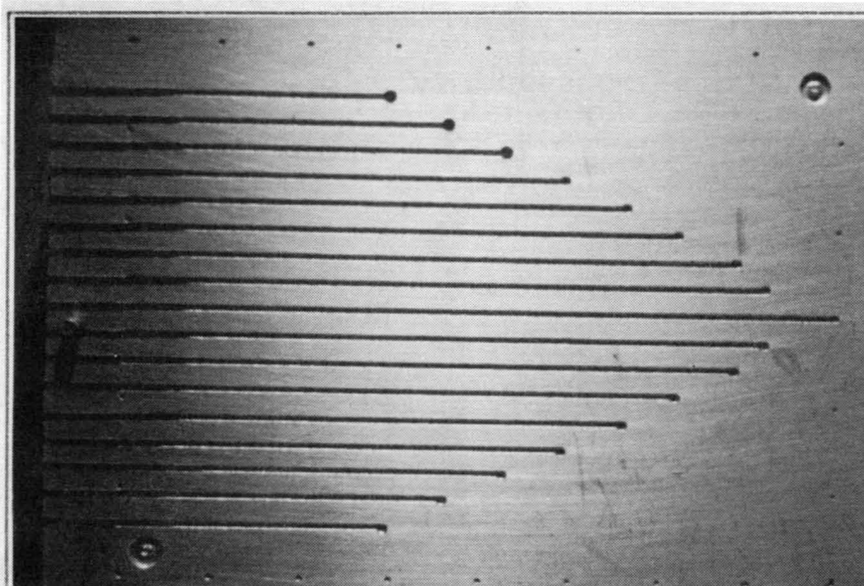


Fig. 3a Layout of chemically milled channels and drilled holes in stainless sample RH2

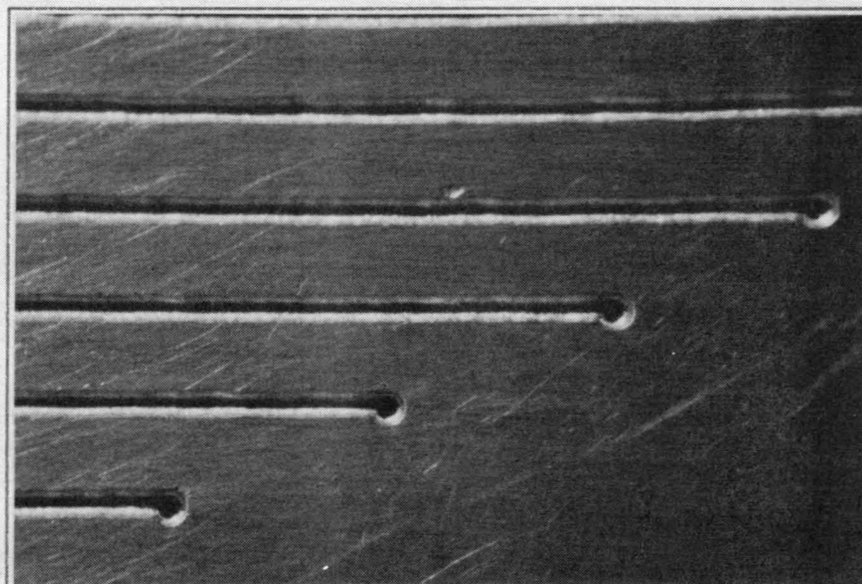


Fig. 3b Higher magnification [X5] view of channels and holes in sample RH2

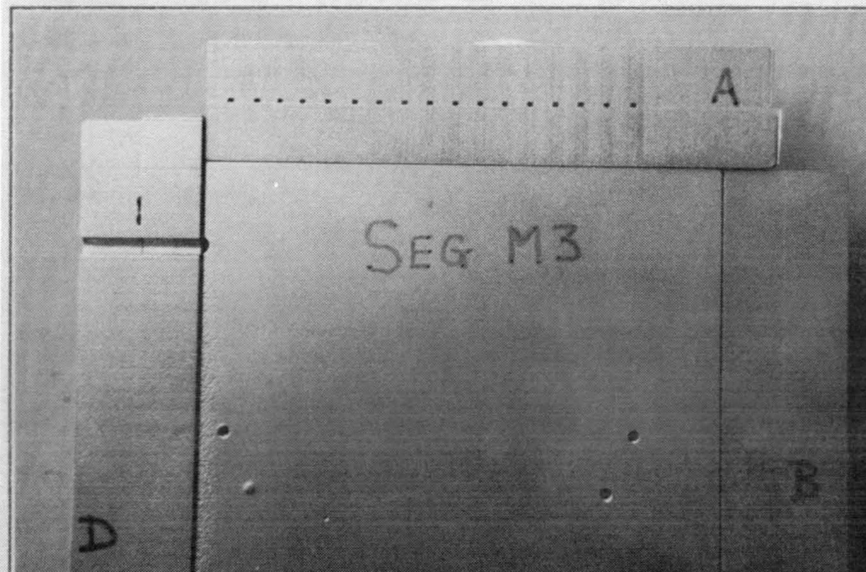


Fig. 3c Location of offcuts 3A, B & D and segment 3M after vacuum brazing sample MG7

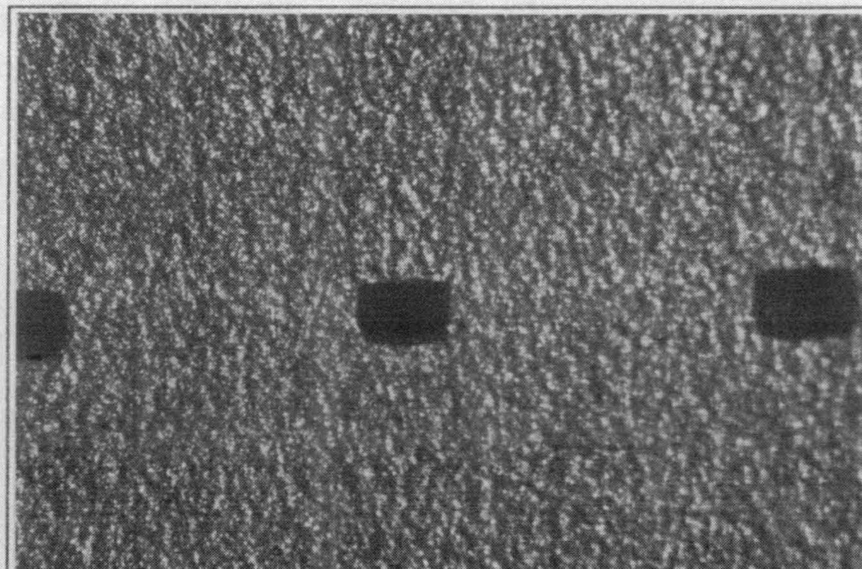


Fig. 3d As wire-cut surface finish of offcut 3A [magnification X20]

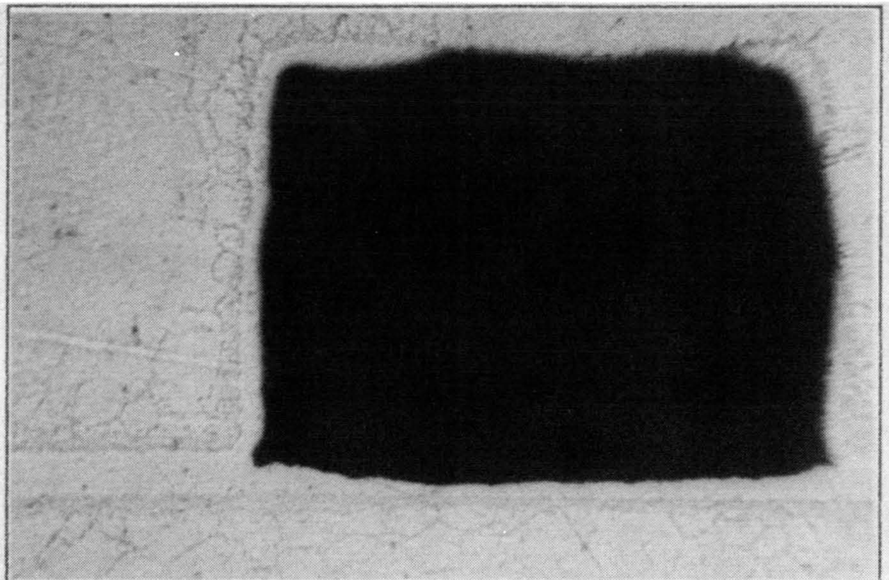


Fig. 4a Offcut 3A polished and etched to show section through brazed joint[magnification X70]

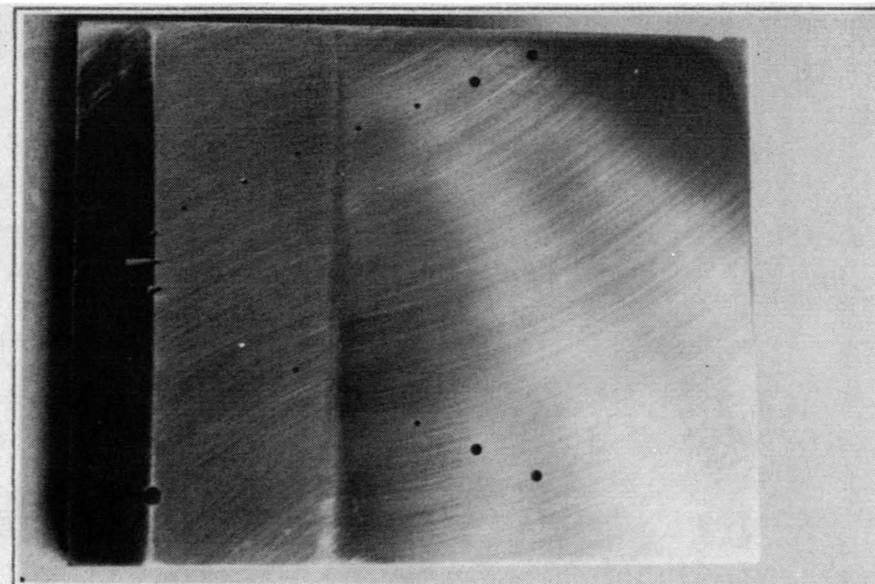
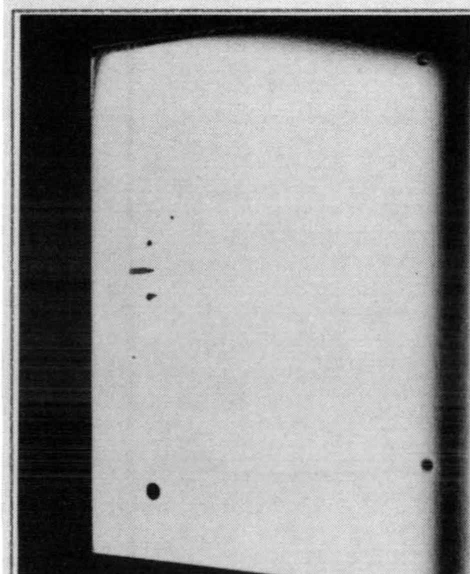


Fig. 4b Segment 3M with 3 planar surfaces ground to expose pre-drilled holes



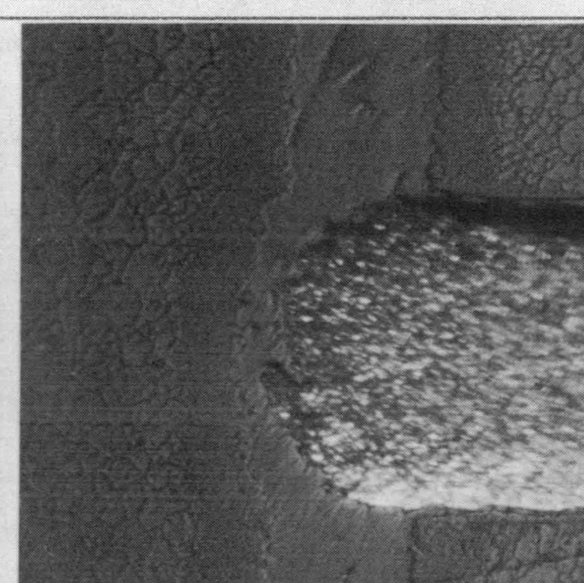


Fig. 4c(left) Segment 3M polished to give taper section through bond line. Fig 4d(center) X10 view of taper section thru bond line & channels. Fig 4e (right) X70 view of center channel.

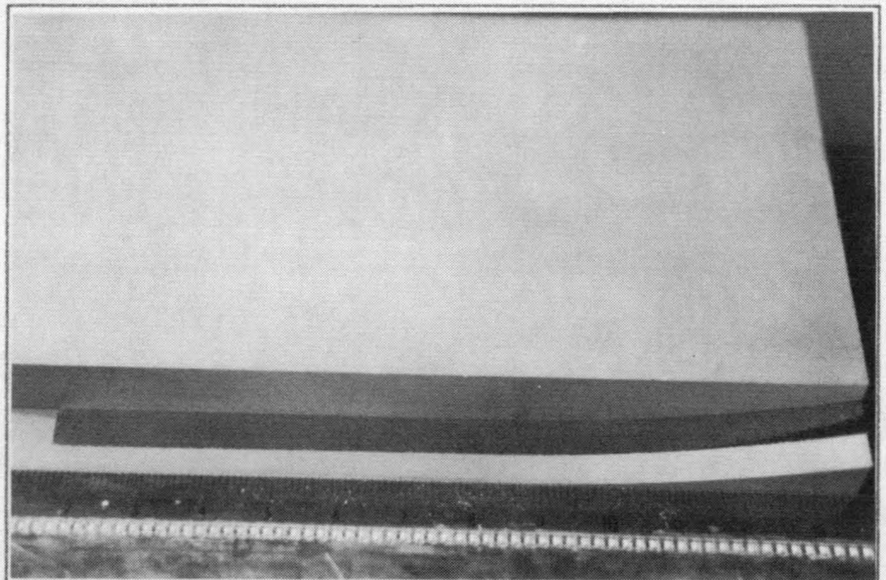


Fig. 5a Samples DS1A&B after wirecutting bond plane, MBF20 braze foil between samples

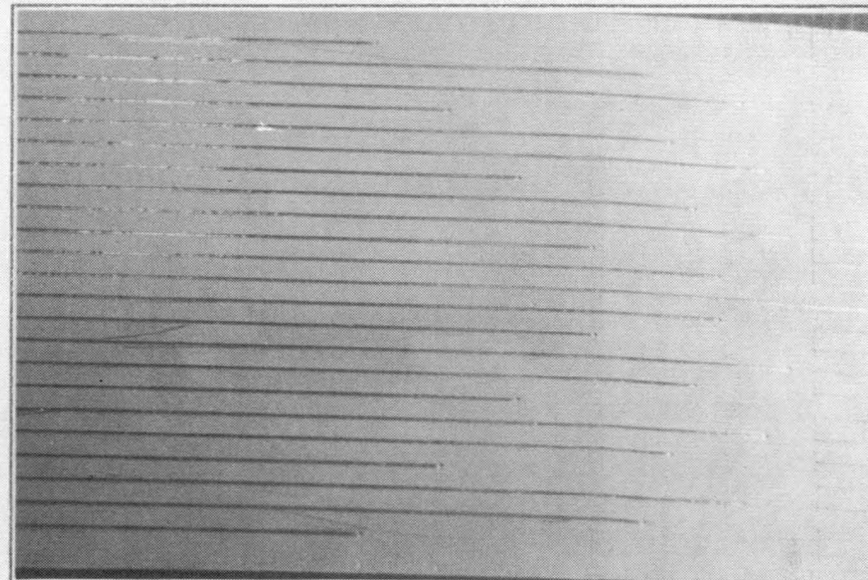


Fig. 5b Channels chemically milled into surface of sample DS1A

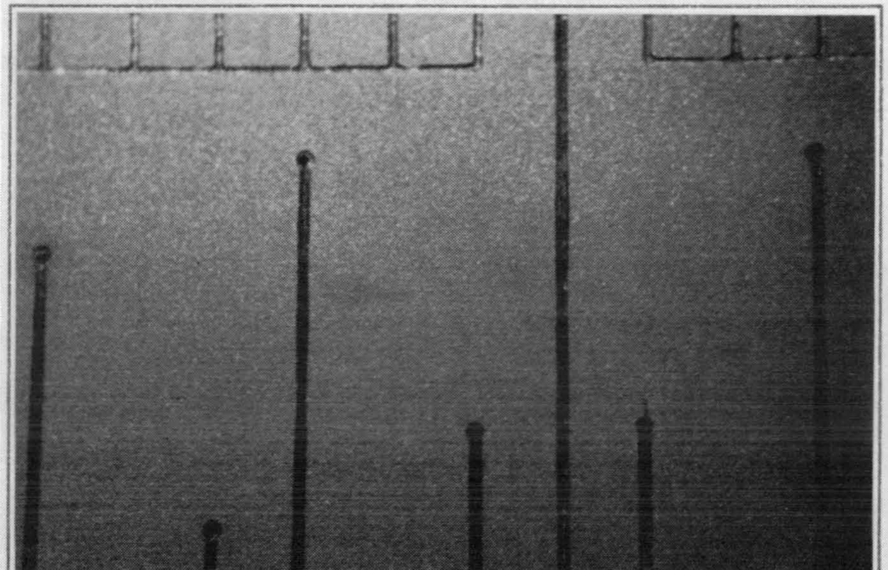


Fig. 5c X4 magnification view of channels and trailing edge locator on sample DS1A

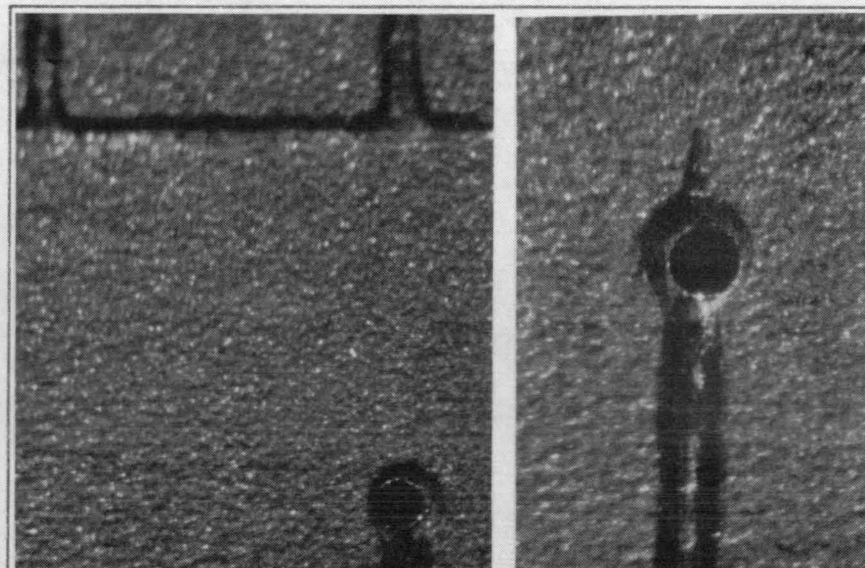


Fig. 5d (left) X15 view of channels & hole. (right) X20 view of .32mm (.013in) hole

Fig. 6a(upper) DS1A&B laser tack welded & brazed. (lower) Chemically milled lettering

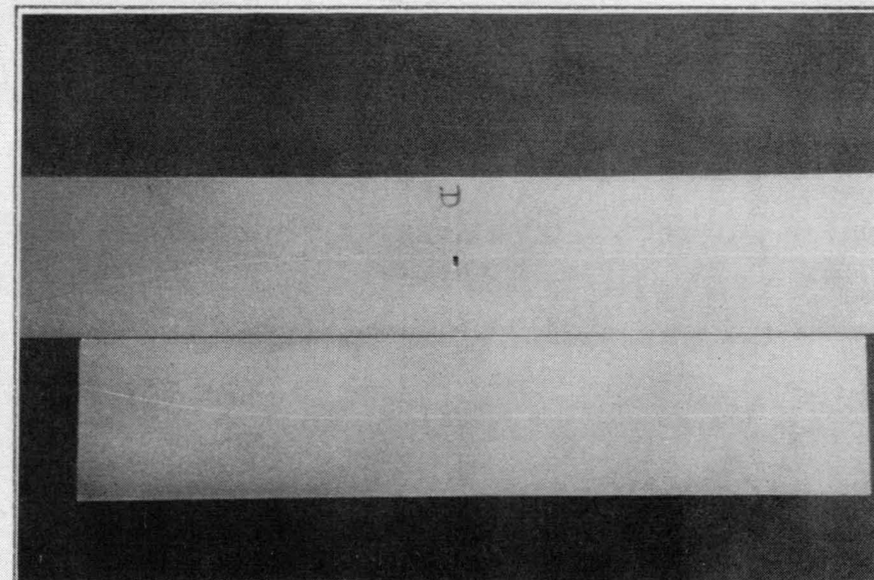


Fig. 6b As-wirecut longitudinal sections thru offcut (upper) & sample DG1/M98 (lower)

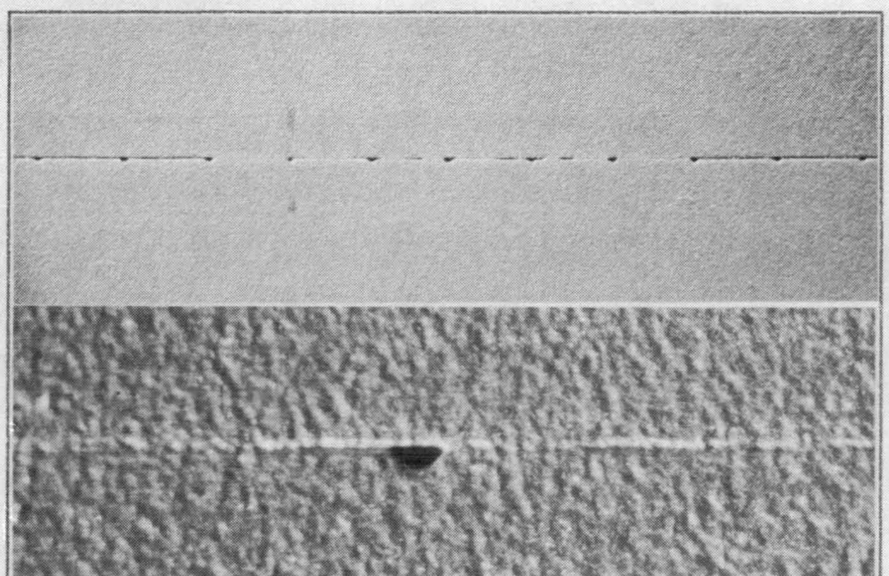


Fig. 6c (upper) As-wirecut section across MG8 channels[X3]. (lower) X15 section thru channel

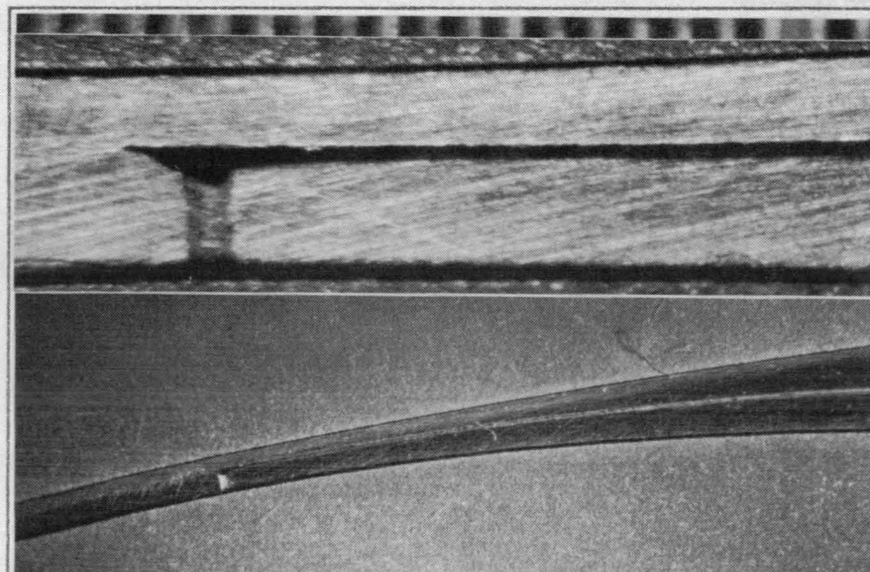


Fig. 6d (upper) Channel & .32mm orifice. [X16] (lower) Location of orifice in airfoil[X4]

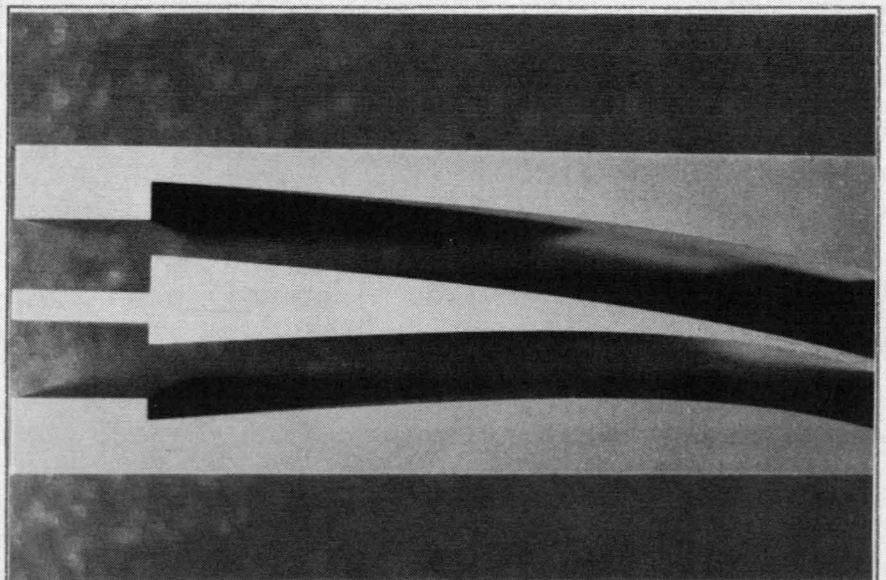


Fig. 7a Segment 4M as-wirecut from sample MG8 shown together with offcuts

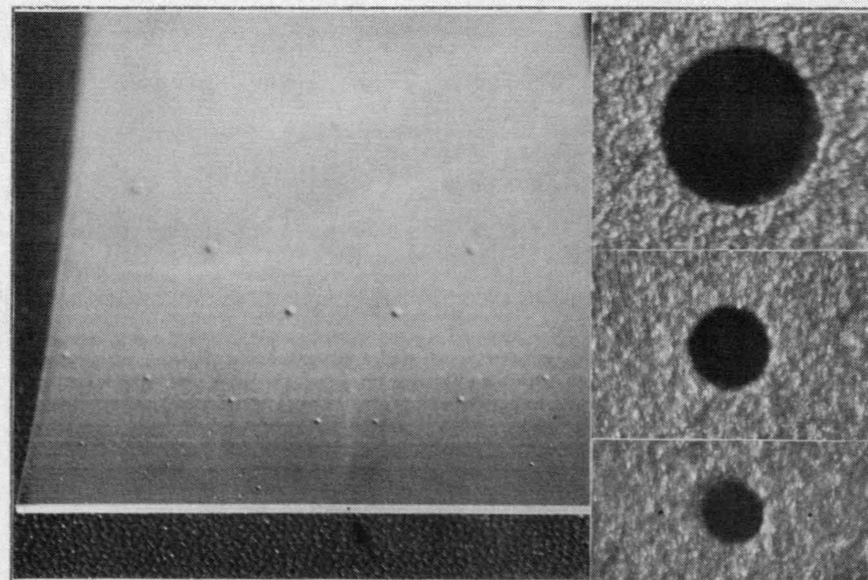


Fig. 7b (left) Orifice in trailing edge. (right) 1, .5 & .32mm (.040, .020, .013in) orifices

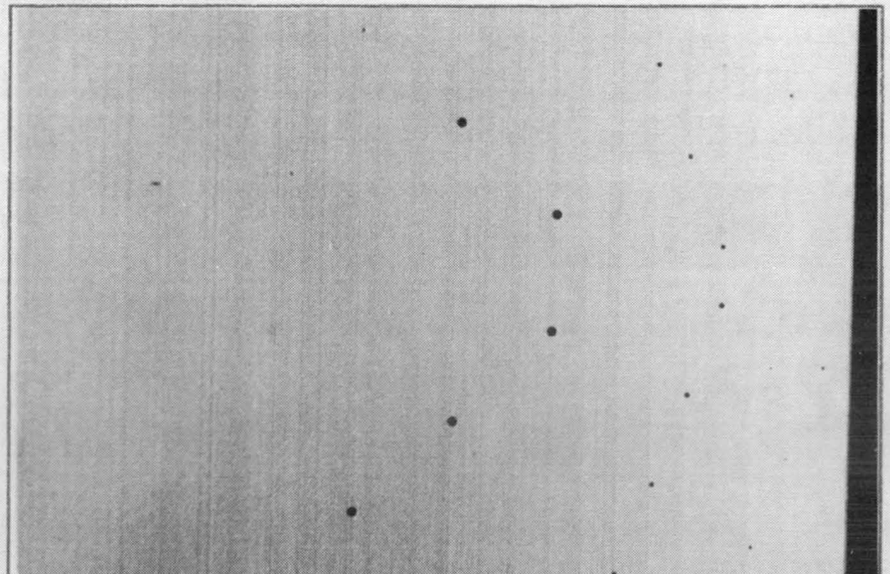


Fig. 7c View of orifices formed by wire cutting profile on lower surface

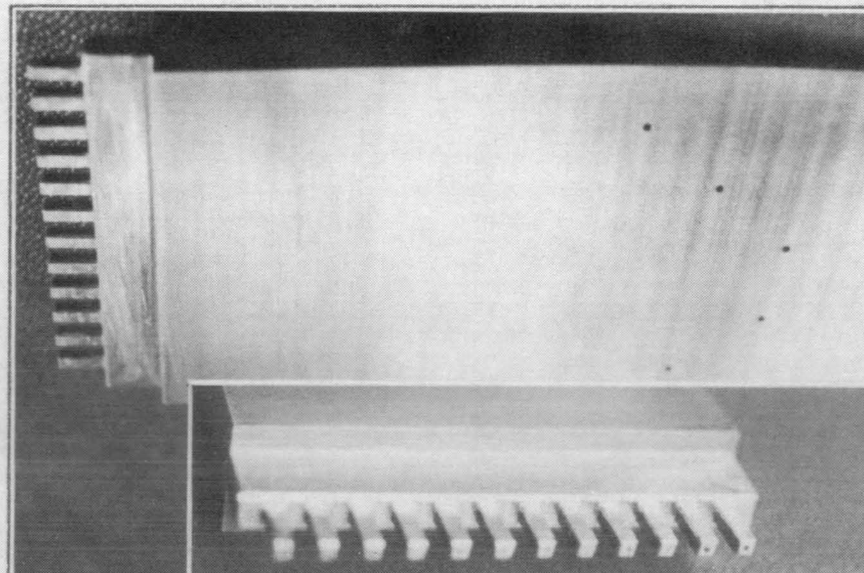


Fig. 7d Combs cut on forward edge of segment 4M. (inset) frontal view of combs

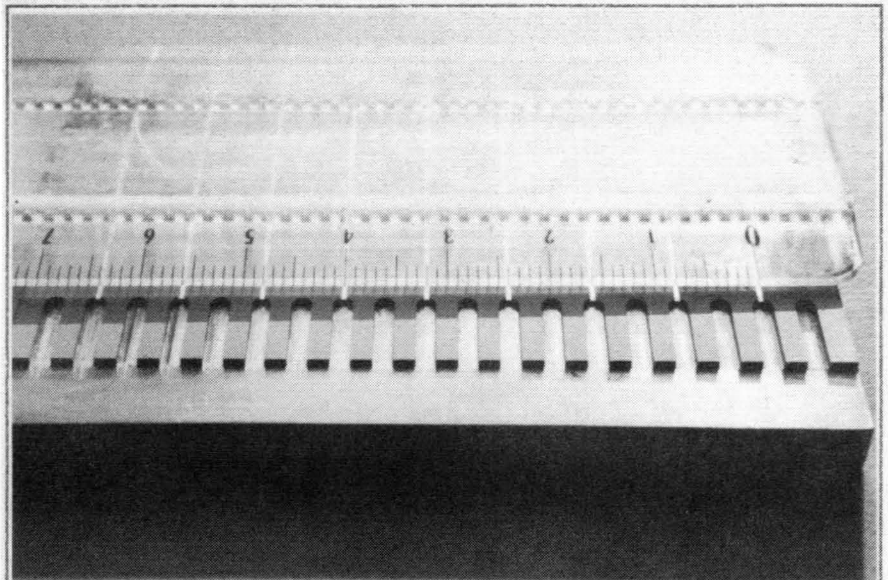


Fig. 8a Sample LJS1 showing 1mm (.040in) deep docking ports milled into 316 plate

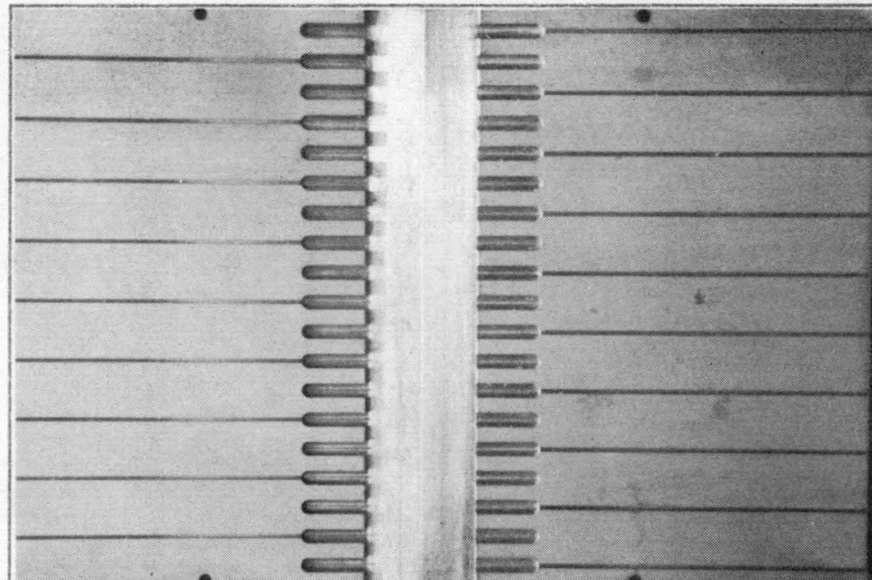


Fig. 8b Samples LJS1&2 showing matching docking ports & .5mm (.020in) channels

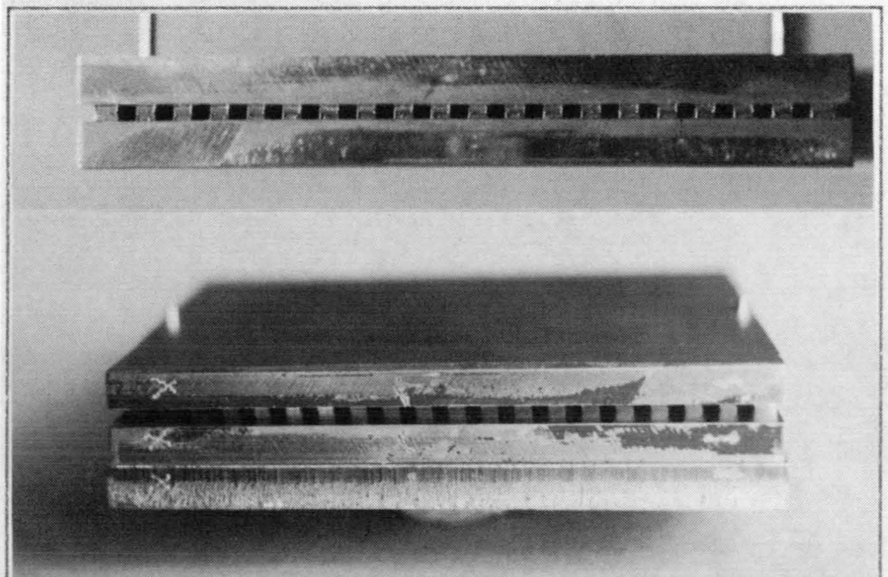


Fig. 8c (upper) LJS1&2 before brazing. (lower) LJS1&2 plus RH1 brazed to form MG6

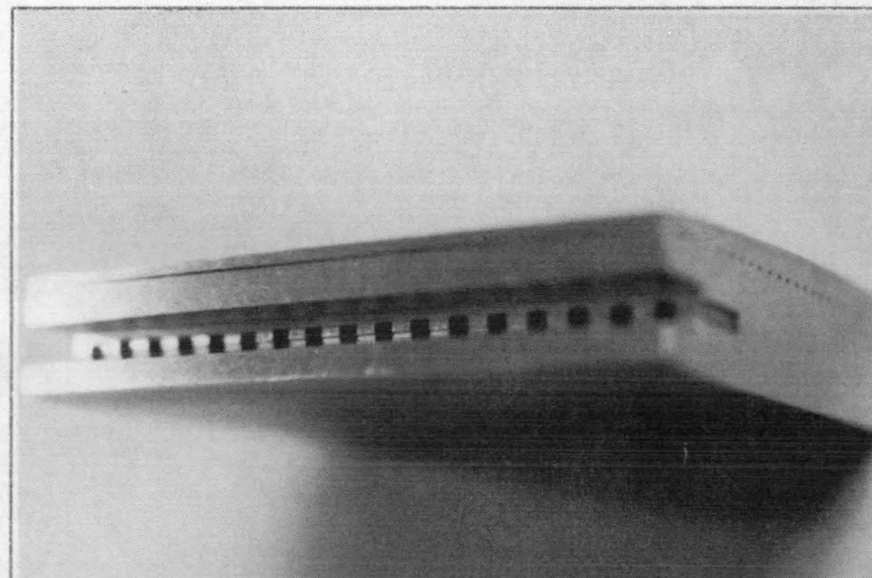


Fig. 8d MG6 cut & shaped to form segment 3F, showing docking ports & cross channels

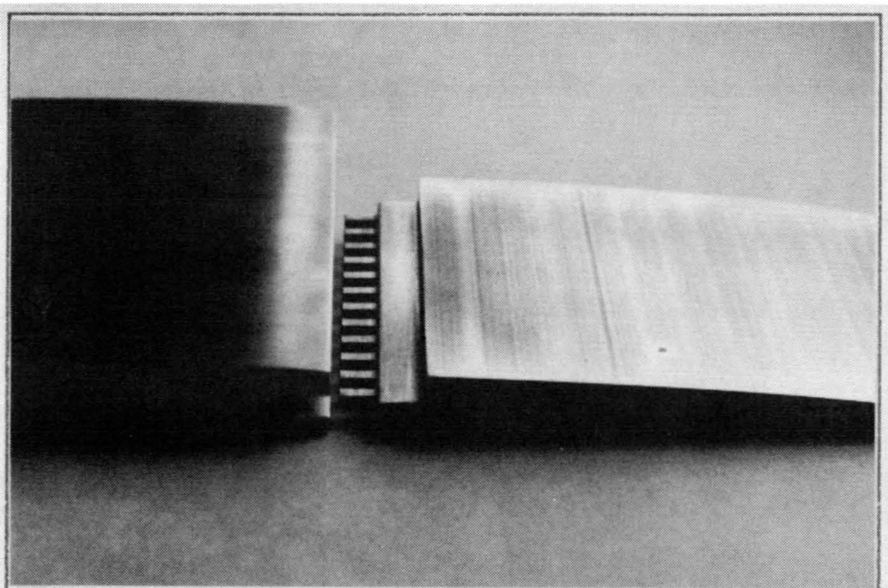


Fig. 9a Segments 3F (left) and 4M (right) before docking

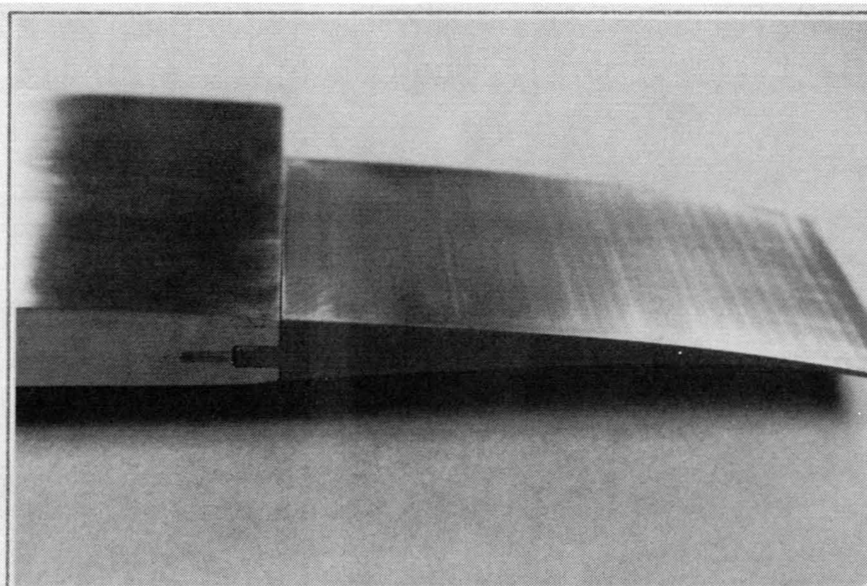


Fig. 9b Segments 3F and 4M after docking

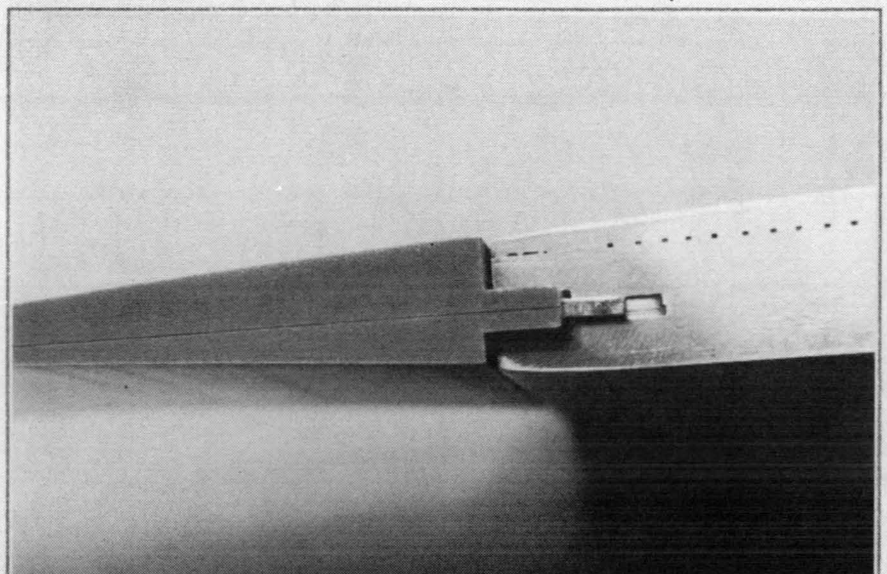


Fig. 9c Segments 3F and 4M laterally shifted by one comb to show joint between channels

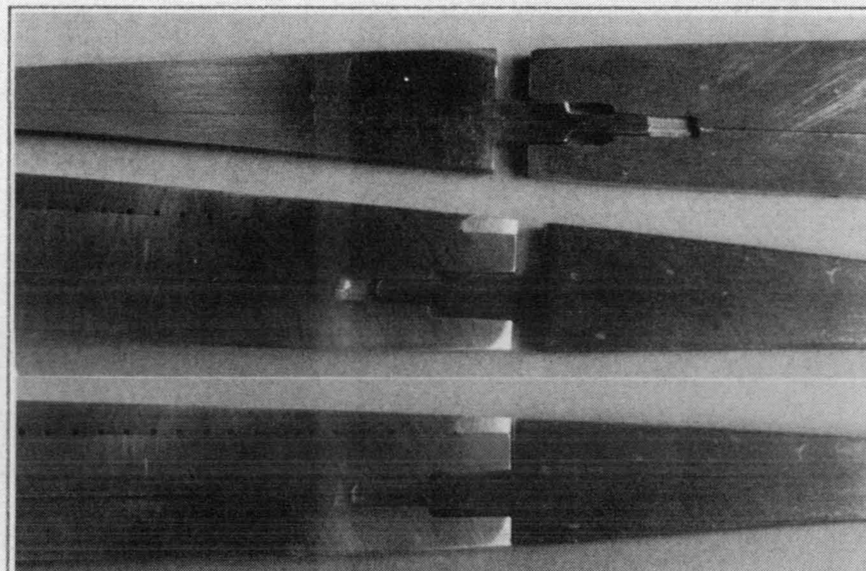


Fig. 9d (upper two) Sections through channel joints undocked. (lower) Docked.

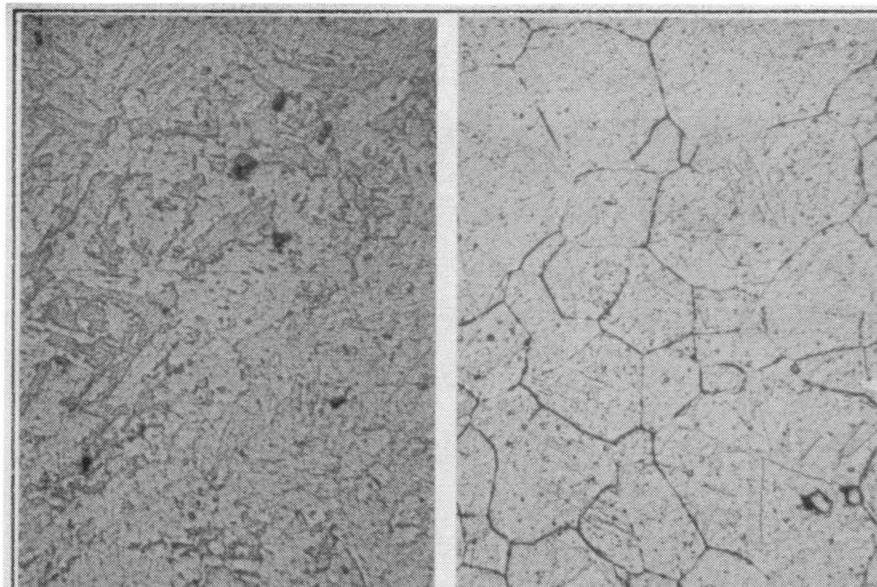


Fig. 10a Vascomax 200 [X400], (left) before & after (right) vacuum brazing at 1050C

Fig. 10b X400 view of Vascomax 200 sample used as control for vacuum brazing tests

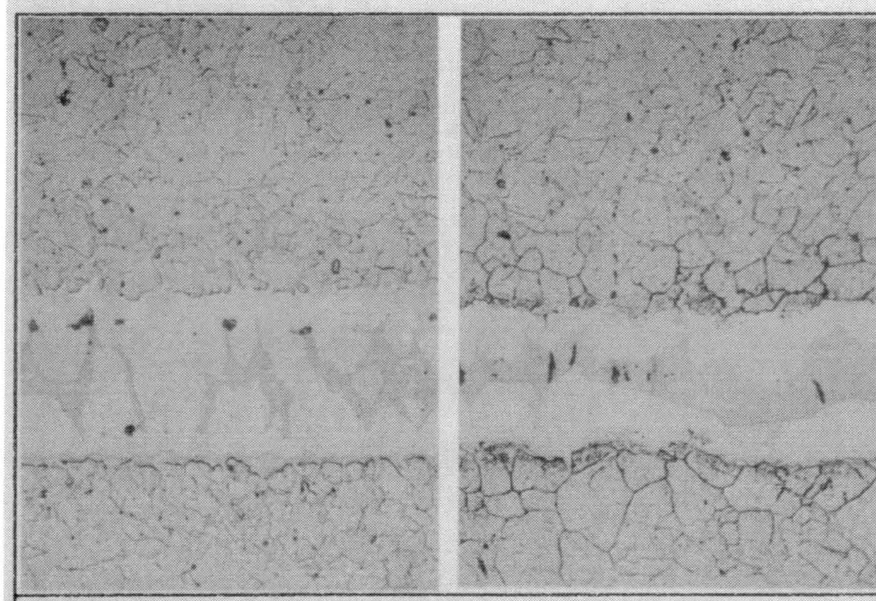


Fig. 10c [X400] vacuum brazed bonds. (left) MBF1005 @927C: (right) MBF65A @982C

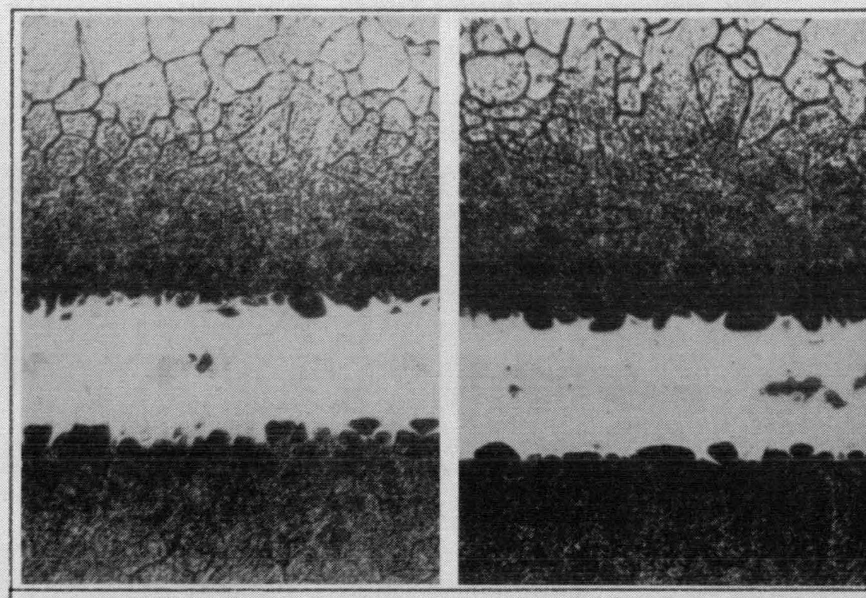


Fig. 10d [X400] vacuum brazed bonds. (left) MBF1002 @1010C: (right) MBF20Mod @1010C

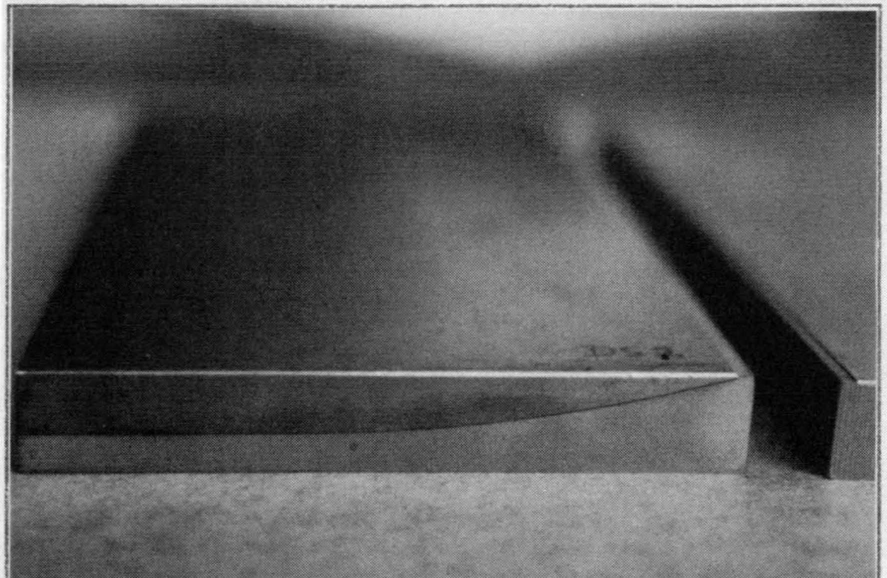


Fig. 11a Samples DS2A&B replaced together after E.D.M. wire cutting

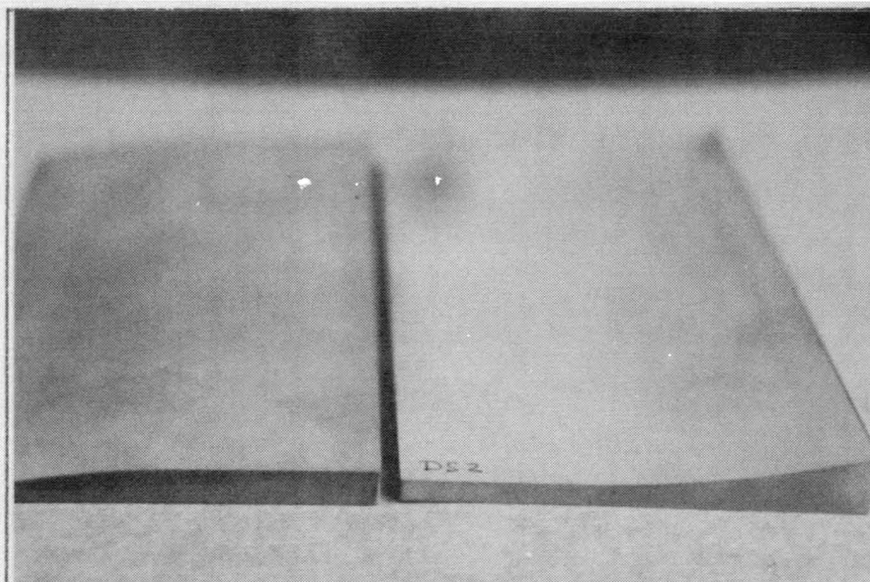


Fig. 11b Samples DS2A&B after EDM wire cutting showing faying surfaces

Fig. 11c Samples DS2B(left) and A(right) after chemically milling channels & drilling holes

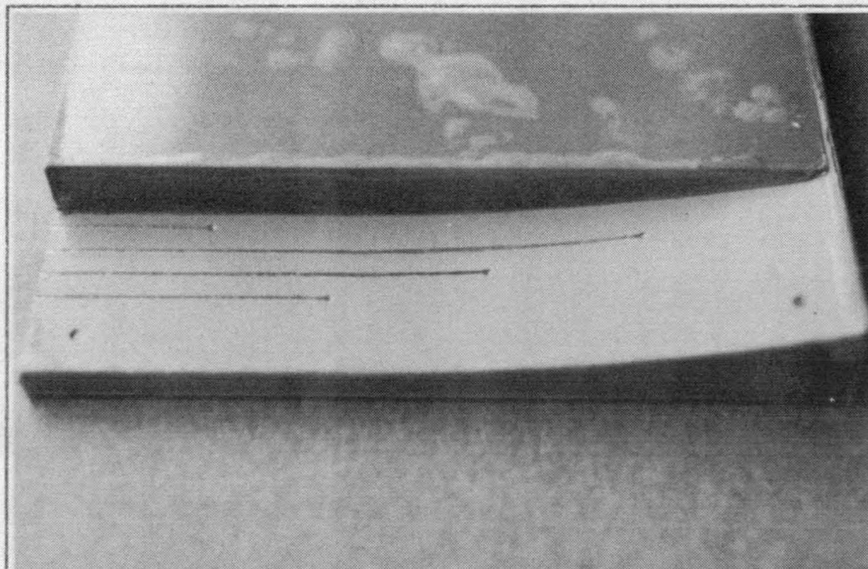


Fig. 11d Samples DS2 A(top) and B(bottom) put together after chemically milling channels

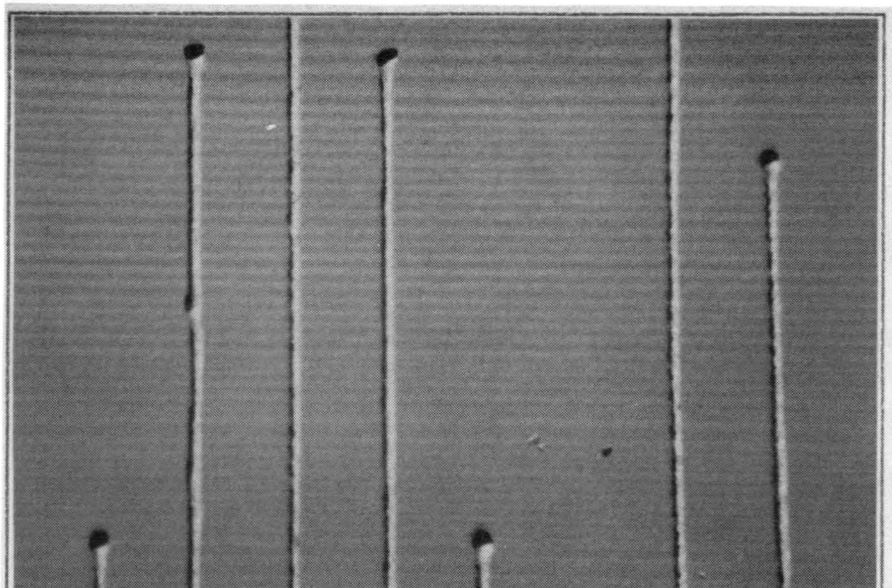


Fig. 12a X4 view of channels as chemically milled but before edge cleaning

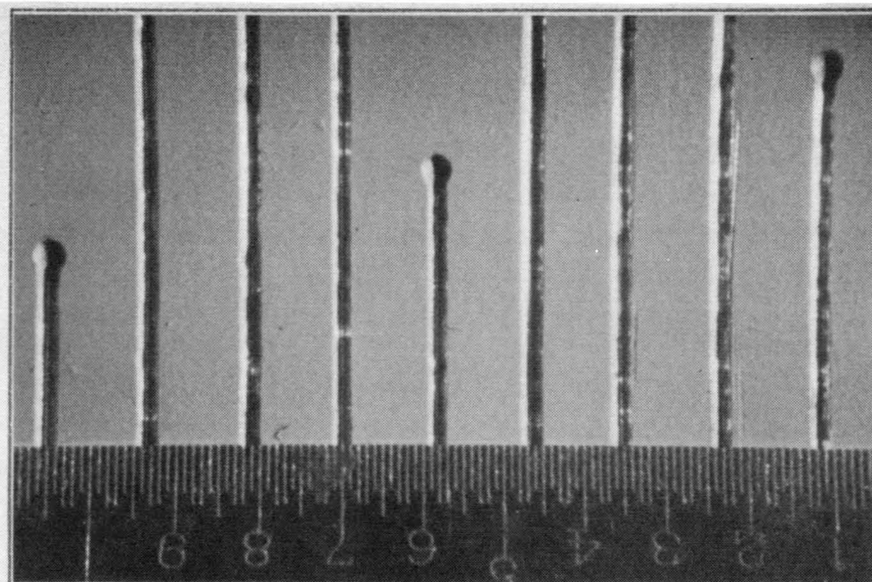


Fig. 12b X4 view of chemically milled channels after cleaning edges with needle file

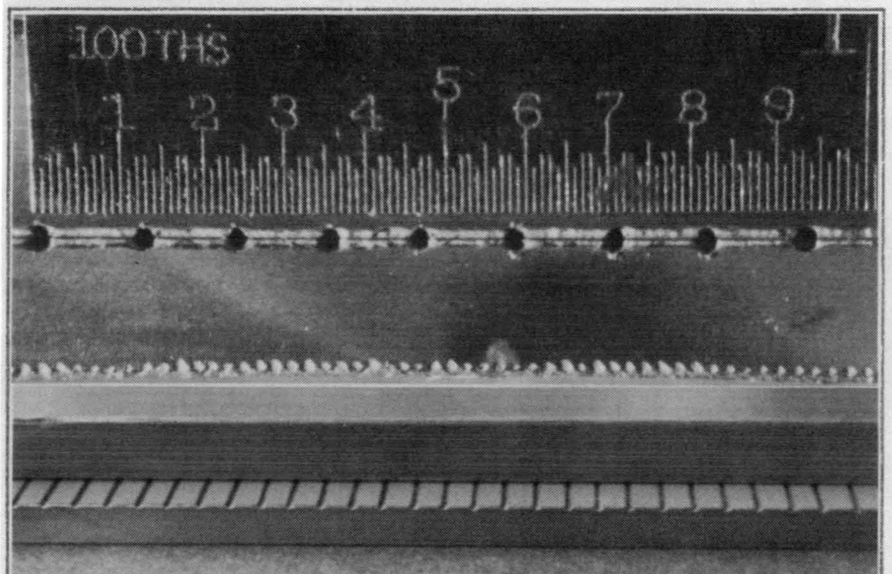


Fig. 12c Views of DS2 A&B showing matched half channels; (top) X4, (bottom) X1.5

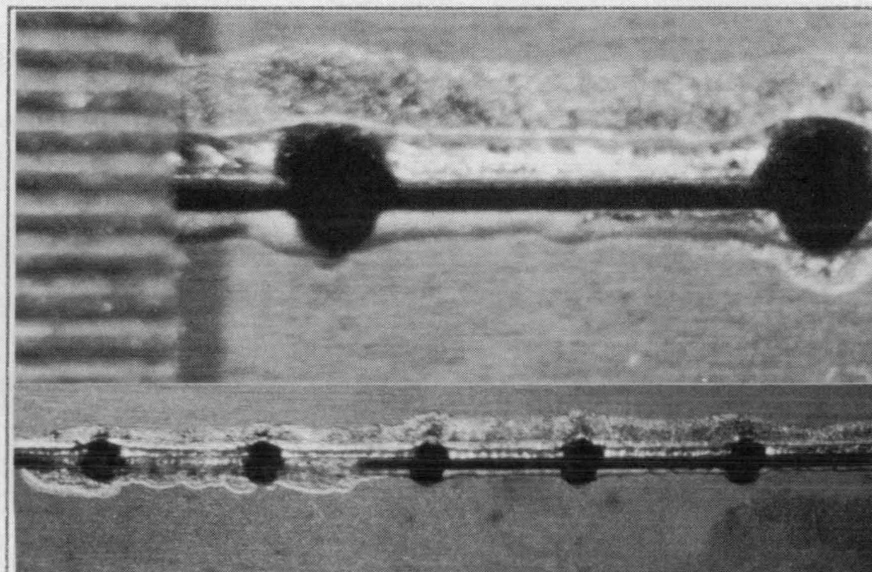


Fig. 12d Views of channels and .25mm gap after brazing; (top) X20, (bottom) X7

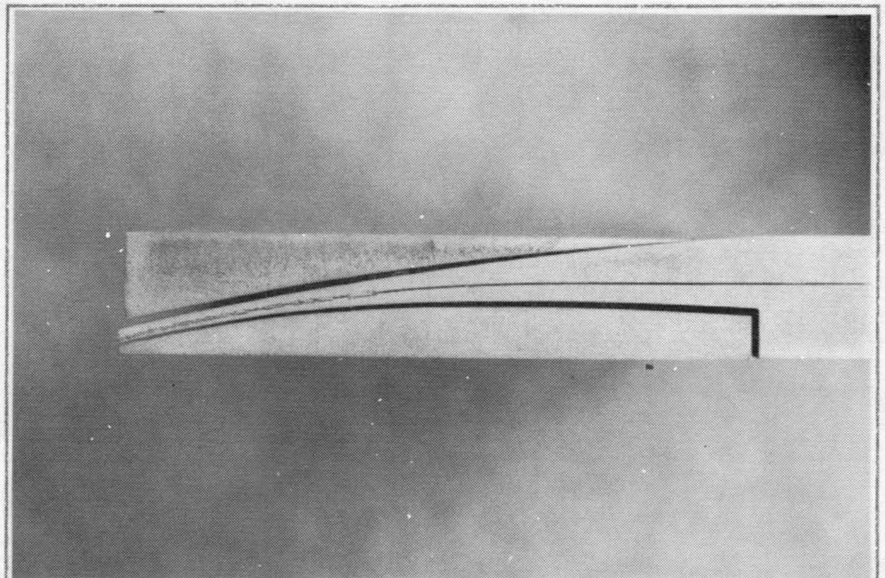


Fig. 13a DS2 A&B after brazing to form MG13 and EDM wire cutting to give segment 5M

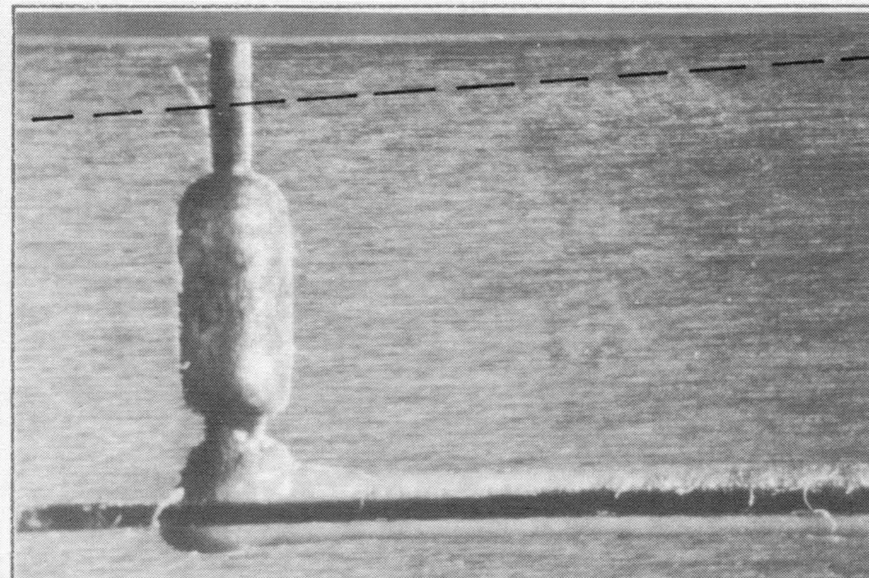


Fig. 13b Section cut from MG13 thru channel & orifice[X15]. Dotted line shows airfoil surface

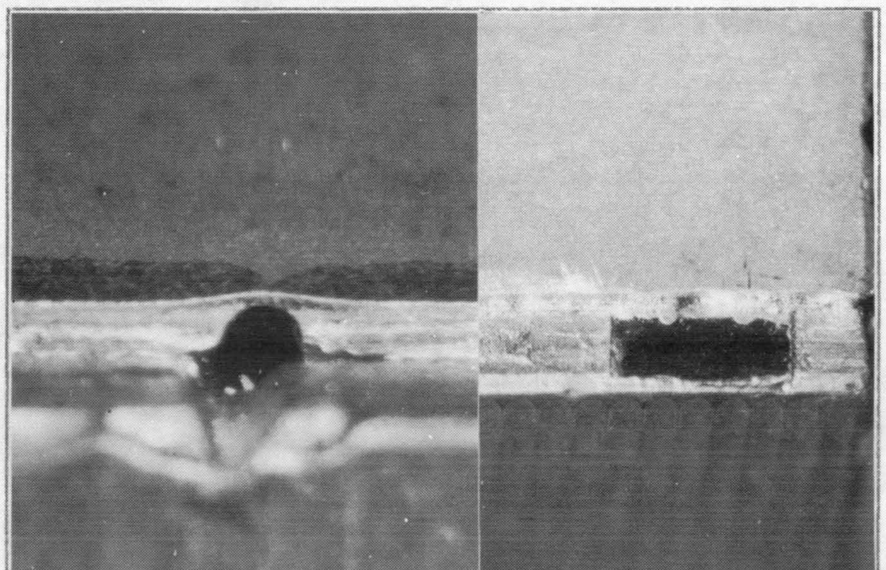


Fig. 13c (left) Trailing edge orifice in MG13 as brazed [X15]: (right).05mm Nickel shim [X12]

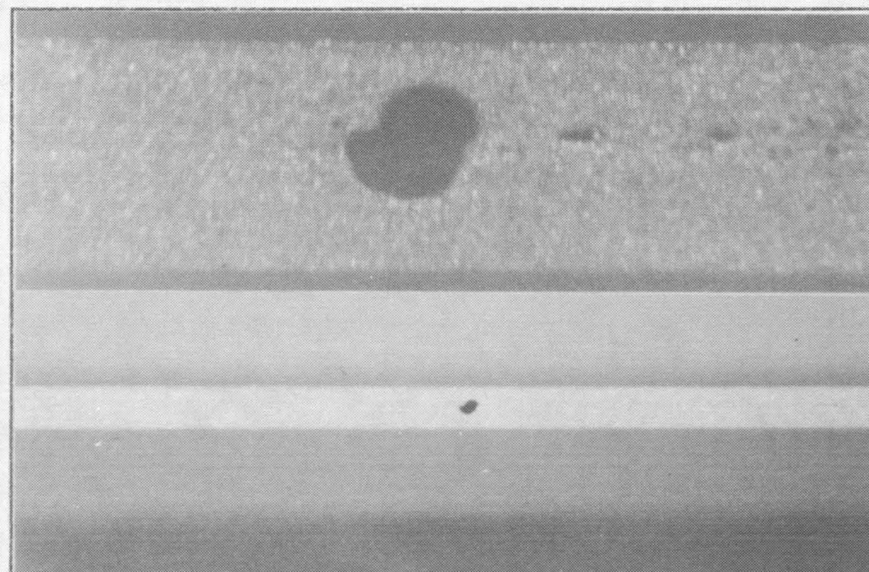


Fig. 13d Trailing edge orifice in segment 5M, as-wirecut. (upper) X15, (lower) X3

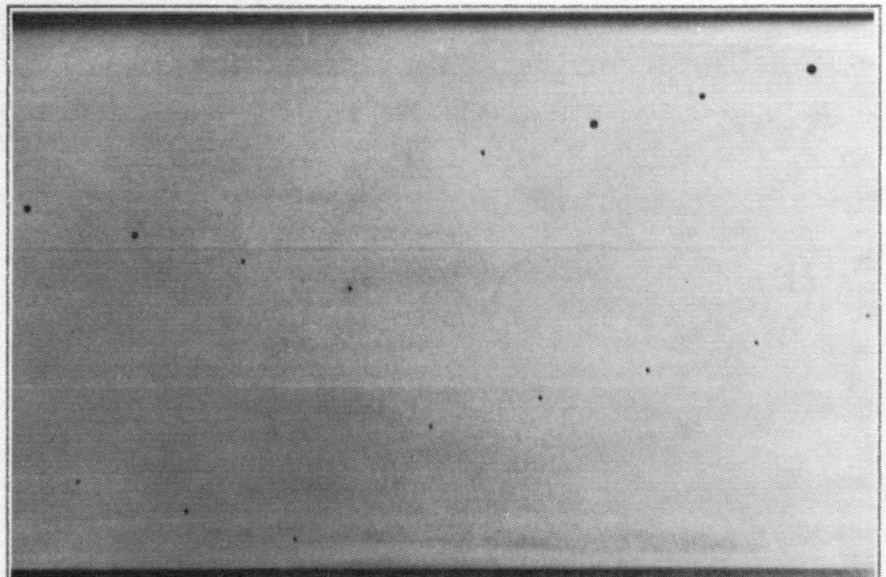


Fig. 14a Segment 5M. View of as—wirecut lower surface showing .32mm (.013in) orifices

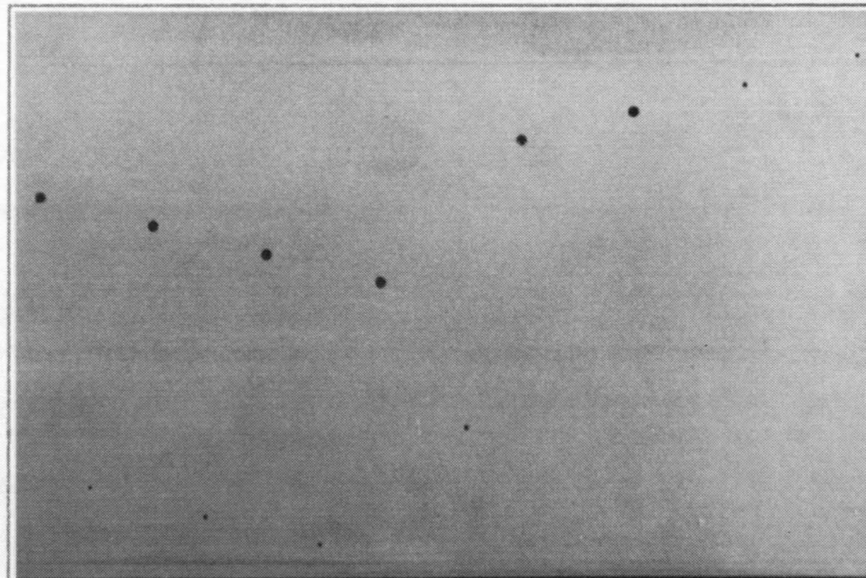


Fig. 14b Segment 5M. View of as—wirecut upper surface showing .32 & 1mm orifices

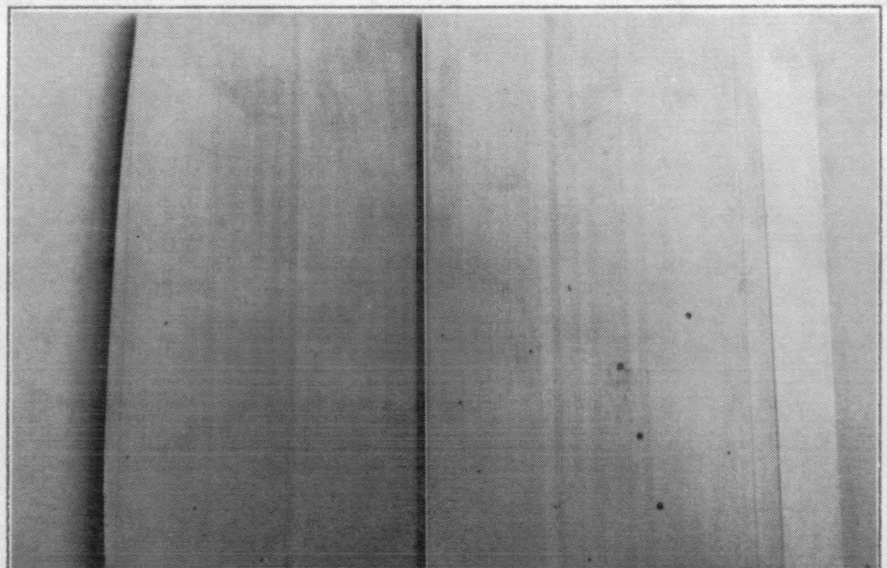


Fig. 14c Segment 6M. View of upper surface (right) & offcut (left) showing warpage effect

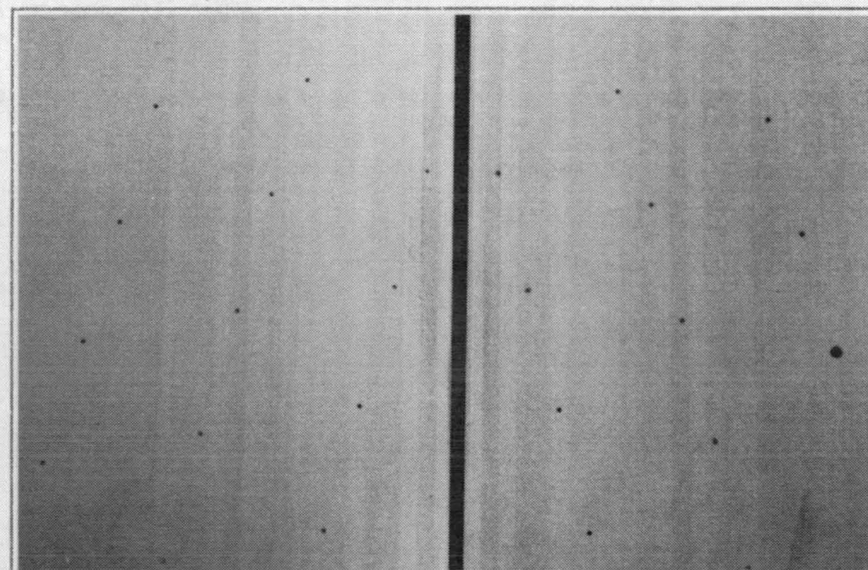


Fig. 14d Segment 6M. View of lower surface (right) & offcut (left) showing orifices[X1.5]

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16. Abstract

A description is given of the elements of the technology required for the production of thin, cambered, two-dimensional, pressure-instrumented airfoils for testing in cryogenic wind tunnels. Experiments were carried out using various combinations of materials and fabrication techniques suitable for constructing thin airfoils containing a network of internal passages connected to pressure orifices in the airfoil surfaces. A network of channels was chemically milled into one surface of a pair of matched plates having bond planes which were neither planar or profiled to match the contour of the trailing edge of a supercritical airfoil. Vacuum brazing was used to bond the plates together to create a network of pressure passages without blockages or cross-leaks. The greatest success was achieved with the smaller samples and planar bonding surfaces. In larger samples, problems were encountered due to warpage created by the relief of residual stresses. Successful bonds were formed by brazing A286, Nitronic 40 and 300 series stainless steels at 1065 C using AMS 4777B brazing alloy, but excessive grain growth occurred in samples of 200 grade 18 nickel maraging steels. Good bonds were obtained with maraging steel using a 47 percent Nickel-47 percent Palladium-6 percent Silicon alloy and brazing at 927 C. Electro-Discharge-Machining was found to be an effective method of cutting profiled bond planes and airfoil contours. Orifices of good definition were obtained when the EDM wire cut passed through predrilled holes. Initial trails were also made of possible configurations for joints between small segments and the larger main wing that would be load-bearing and capable of incorporating leak-free joints between the pressure passages in both components.

17. Key Words (Suggested by Author(s)): Wind tunnel models; Cryogenic tunnels; Cryogenic materials; brazing; joining; metallurgy

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